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EVALUATION OF HYDRAULIC FLUIDS FOR USE IN ADVANCED SUPERSONIC AIRCRAFT

by

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ABSTRACT

MCS-293 modified polyphenyl ether, PR-143AB fluorocarbon, MLO 60-294 superrefined mineral oil, F-50 silicone, and MCS-3101 halogenated polyaryl are candidate hydraulic fluids being evaluated for use in advanced supersonic aircraft. Pertinent properties have been determined and evaluated for potential use at fluid temperatures up to 600°F at the pump inlet. A Shell Four-Ball Wear Tester was converted to a rider-on-disk boundary lubrication tester. Selection of pump bearing materials will be made for each fluid based on tester results. Fluids will be screened in simple pump loops at 400°, 500°, and 600°F with pump discharge pressures of at least 3000 psi. The two fluids which perform best will be endurance tested in a complete hydraulic system for 3000 hours at a selected maximum temperature and pressure.

Author

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EVALUATION OF HYDRAULIC FLUIDS FOR USE IN ADVANCED SUPERSONIC AIRCRAFT

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SUMMARY

This report describes the work accomplished during the first six months of NASA Contract NAS 3-7263, ending 30 September 1965. Activities during the reporting period included:

(1) Evaluation of the properties of candidate hydraulic fluids

(2) Preparations for conducting lubrication tests of candidate pump bearing materials.

Properties of five selected fluids and some of the properties of three other fluids were evaluated and compiled. Fluids evaluated were General Electric's F-50 silicone, Monsanto's MCS-293 modified polyphenyl ether and MCS-3101 halogenated polyaryl, Humble Oil's FN 3160 superrefined MLO 60-294 mineral oil, and DuPont's PR-143AB fluorocarbon. Initial properties of interest included thermal stability, fire resistance, bulk modulus, viscosity, density, specific heat, thermal conductivity, nitrogen solubility, and compatibility.

The evaluation was conducted with data obtained from tests at Republic and from vendor sources. Preliminary merit ratings of the fluids, based on their suitability for use in a 600°F hydraulic system, in decreasing order are as follows: MCS-293, PR-143AB, MLO 60-294, F-50, and MCS-3101.

In preparation for the lubrication tests, a Shell Four-Ball Wear Tester was converted to a rider-on-disk boundary lubrication tester. The conversion permits the evaluation of pump bearing materials under conditions that are more representative of actual usage than was possible with the previous configuration. Checkout of the unit was completed just prior to the end of the reporting period.

INTRODUCTION

Future advanced supersonic aircraft will present difficult technological problems associated with high operating temperatures. Further complication arises from stringent requirements for long-term integrity and economical operation.

Reliable operation of flight controls and utilities is one of the major problem areas. Selection of a power transfer medium largely determines the subsequent design and performance characteristics of the system. The fundamental goal of this program is the selection of hydraulic fluids suitable for 3000 hours of reliable operation in a temperature range of -40° to +600°F and hot spots to 650°F.

Several experimental hydraulic fluids that approach the design requirements are available; several others are currently being developed. Experience has shown that the most realistic evaluation of a fluid's potential is accomplished through simulated system testing with optimized aircraft-type pumps.

This program is divided into four tasks:

Task I	-	Selection and property determination of five fluids
Task II	-	Determination of optimum pump bearing materials by boundary lubrication tests
Task III	-	Screening of candidate fluids in a simple pump loop
Task IV	-	Endurance testing in a simulated system of the best two fluids as determined in Task III.

TASK I - DETERMINATION OF PHYSICAL AND CHEMICAL PROPERTIES OF SELECTED FLUIDS

A. SELECTION OF HYDRAULIC FLUIDS

The following five fluids were initially selected for evaluation:

(1) F-50, a chlorinated phenyl methyl silicone (General Electric)

(2) MLO 60-294, a deep-dewaxed superrefined paraffinic base oil (Humble Oil's FN 3160)

(3) MCS-310, a halogenated polyaryl (Monsanto)

(4) MCS-293, a modified polyphenyl ether (Monsanto)

(5) PR-143AB, a fluorocarbon (DuPont)

A glossary of product designations is included at the end of this report.

F-50 silicone was selected as a reference fluid because of its extensive use in high temperature hydraulic system development. Disadvantages of this fluid are its marginal lubricating properties and low bulk modulus. On MLO 60-294 mineral oil, performance data is limited in the range of current interest. One serious deficiency of mineral oils is their poor fire resistance.

MCS-310 polyaryl fluid was specifically formulated as a high-temperature fire-resistant hydraulic fluid. It was previously pump-tested by Douglas Aircraft (Reference 1) at a 400°F pump inlet temperature for 100 hours. Limited data indicated it to be worthy of further consideration. An additive was recently incorporated in its formulation to improve its performance in a servo valve test. The reformulated fluid, MCS-3101, replaced MCS-310 for evaluation in the current program.

MCS-293, an engine oil grade polyphenyl ether was also considered for use as a hydraulic fluid. Previous experience with this class of fluids (Reference 2) has shown some promising results. The viscosity range required of an engine lubricant is in conflict, however, with the relatively low viscosity range required of a hydraulic fluid, especially at the low temperature end of operation. A compromise in fluid properties may prove marginal for either application. However, special component or system design considerations may enable the high viscosity fluid to be pumped at low temperatures. The primary advantage of a dual-purpose single fluid is simplified logistics.

PR-143AB fluorocarbon was the most recently developed of the original group of fluids. Its high thermal stability and fire resistance favored its consideration despite a lack of data on most of its other properties. Some known drawbacks at the time of selection were its high density and cost.

Some of the other fluids available at the time of selection were:

(1) XRM-154, an alkylated silicone (Socony Mobil)
(2) XF-1-0288, a copolymer of trifluoropropyl and bromophenyl methyl silicone (Dow Corning)
(3) B-88A/64, a brominated hydrocarbon-ester mixture (Castrol)
(4) ETO 5251, an ester-base oil (Humble Oil)
(5) HTHF 70, a silicate ester fluid (Chevron Chemical)
(6) Fluorinated alkoxy phosphonitrilates (Olin)
(7) Synthetic 18H, a polyolefin (Sun Oil)

These fluids were bypassed because of either poor thermal stability or insufficient data on which to evaluate their capabilities.

During the course of this program, new fluids will be constantly kept under surveillance. These include:

(1) XF-1-0291, which is XF-1-0288 with a defoamer (Dow Corning)
(2) XF-1-0294, a trifluoropropyl methyl silicone (Dow Corning)
(3) XRM-154D, an alkylated silicone (Socony Mobil)

B. PROPERTIES OF FLUIDS

1. Test Methods

Some of the test methods for determining pertinent properties of fluids are listed in Table 1. Properties were defined by standardized methods in some of the cases. Lack of complete standardization stems either from difficulty in setting up test procedures or from lack of agreement on the significance of particular tests.

Reasons for using specific test methods will be briefly discussed below.

Thermal stability was determined by the stainless steel tube method, in which a fluid is heated for a prescribed time at a constant temperature in a stainless steel tube and in the absence of oxygen. The fluid is degassed and the air in the tube is replaced with purified nitrogen.

This test method gives reasonable indication of fluid life in a hydraulic system. The stainless steel tube is representative of corrosion-resistant materials used in the system. Its use permits the retention of decomposition products in the test apparatus, which is typical of another hydraulic system condition. Detrimental effects on the base fluid by the decomposition products will be evident through the measurement of changes in viscosity and acid number. These property changes are meaningful to designers. The philosophy of simulating representative aircraft conditions may also be applied to material compatibility test methods.

The significance of various standard fire resistance tests has been the subject of considerable debate. Existing methods include the spray ignition, hot manifold, autoignition, flash and fire point, and hot chamber spark tests. All but the hot chamber test are employed in this program. The question arises as to how representative these tests are of aircraft conditions. Caution must be used in the interpretation of results; however, some indication of the relative fire resistance of various fluids can be obtained by the above tests.

The assessment of fluid lubricating ability is complex. For example, reciprocating piston rods, pump bearings, gears, etc., impose dissimilar lubrication requirements on the fluid. A large gap exists in correlating bench test results with

TABLE 1. TEST METHODS FOR DETERMINING HYDRAULIC FLUID PROPERTIES

Test	Test Specification		
	ASTM	FTM Std. No. 791	Others
Thermal stability			
a. Stainless steel			
b. Glass tube	D2160-63T		WADC TR 55-30 P. VIII, "Fluids Lubricants, Fuels and Related Materials"
c. Isoteniscope			Industrial and Engineering Chemistry, Vol. 1, No. 1, March 1962, "Thermal Stability of Organic Compounds," I.B. Johns et al. pp 2-6.
d. DTA			
Flash point	D 92-57	1103.5	
Fire point	D 92-57	110.35	
Autogenous ignition temperature	D 286-58T	1152	
Hot manifold test		6053-T	AMS-3150C, MIL-F-7100
Ignition spray test		6052-T	AMS-3150C, MIL-F-7100
Incendiary gun fire test			MIL-F-7100
Molten metal pour test			Method under investigation by ASTM
Pipe cleaner burner test			MIL-F-7100
Tonawanda spoon test			Method investigated by ASTM
Hot chamber spark test			Under investigation by Boeing and others
Viscosity	D 445-64	305.3	
Neutralization number	D 664-58	5106.3	
Pour point	D 97-57	201.7	
Density	D 941-55	402.1	
Foaming tendency	D 892-63	3212	

TABLE 1. (Continued)

Test	Test Specification		
	ASTM	FTM Std. No. 791	Others
Nitrogen solubility			ML TDR 64-68, "Fluids, Lubricants, Fuels and Related Materials," Pennsylvania State University
Shear stability			MIL-H-8446
Evaporation loss	D972-56	351.1	
Dielectric strength	D 877-		
Oxidation stability	D 943-54	5308.4	
Hydrolytic stability		3457-T	
Bulk modulus a. P-V-T b. Ultrasonic			ASTM Bulletin, Jan. 1959, "Measurement of Bulk Modulus of Hydraulic Fluids," R. Peeler and J. Green ASTM Paper, "The Ultrasonic Determination of the Bulk Modulus of Hydraulic Fluids at Elevated Temperatures and Pressures" ASD-TDR-63-539, "Isothermal Secant and Tangent Bulk Modulus of Selected Hydraulic-Type Fluids to 750°F and 10,000 psig," Midwest Research Institute NCIH, Vol. XIV, 1960, "Hydraulic Fluid Bulk Modulus - Its Effect on System Performance and Techniques for Physical Measurement," L.H. Smith Jr., et al.
Materials compatibility			
Lubricating ability a. Shell 4-Ball b. Timken c. Falex d. Ball-on-disk e. Almen f. SAE machine			

TABLE 1. (Continued)

Test	Test Specification: ASTM	FTM Std. No. 791	Others
Specific heat a. Calorimetry b. Drop method of Mixtures			WADD TR 60-898 Pt. II, "Fluids, Lubricants, Fuels and Related Materials," Pennsylvania State University
Thermal conductivity a. Hot wire method			WADC TR 58-405, "Thermal Conductivity of Lubricating Oils and Hydraulic Fluids," University of Michigan AFML-TR-65-112, Fluids, Lubricants, Fuels and Related Materials, Pennsylvania State University Chemical and Engineering Data, Vol. 2, No. 1, Thermal Conductivity of Some Organic Liquids - High Temperature Measurements, Monsanto Chem. Co.
Storage Life			ASD TR 61-144, Accelerated Storage Stability Tests, E.N. Cart Jr., Aeronautical Systems Division
Toxicity			Oral, subcutaneous, and inhalation tests
Surface tension			DeNuoy Tensiometer
Vapor pressure a. Isoteniscope			WADC TR 54-532, Pt. III
b. DTA			DuPont Thermogram, Vol. 2, No. 1, Jan. 1965, Application of the Clausius-Clapeyron Equation to DTA

performance of the end items. However, the bench tests can establish approximate relative performance between various candidate bearing materials when a single test apparatus is used. The absolute test of a fluid-bearing combination must be accomplished with actual system hardware.

In measuring the bulk modulus of a fluid, both the P-V-T and sonic methods appear valid. Isothermal secant bulk modulus data (P-V-T method) is more appropriate for slow moving, high pressure drop conditions. Adiabatic bulk modulus data (sonic method) is more suitable for fast acting conditions with minor pressure fluctuations around the nominal system pressure valve. Data for this program is vendor supplied; the test method varies with the particular supplier. Consequently, allowance must be made for the inherently higher bulk modulus values yielded by the sonic method.

Kinematic viscosity measurements at atmospheric pressure may be accurately determined. When measurements are made at high temperatures, the Ubbelohde viscometers have been found to be the most satisfactory.

The standard neutralization number test method was used, except that a modification was required with PR-143AB fluid to make the fluid soluble.

Air solubility in the fluid by gas chromatographic and gas evolution techniques (Reference 3) were employed by the fluid vendors in obtaining solubility data.

Specific heat and thermal conductivity properties were supplied by the fluid vendors. Data were obtained by calorimetry, drop method of mixtures, hot wire, and parallel plate methods, described in References 4 to 7.

Vapor pressure of fluids may be determined by the isoteniscope and by the DTA methods (References 8 and 9). DTA determinations were performed by Republic.

2. Test Data

a. Thermal Stability

The stainless steel tube and the differential thermal analyzer apparatus (DTA) were used at Republic in thermal stability studies. Fluid manufacturers' data on thermal stability, obtained by other methods, are also included.

All fluids tested at Republic were degassed for 72 hours at 200°F and one micron of mercury pressure prior to use. The degassing apparatus, shown schematically in Figure 1, consists of a one-liter pyrex container filled with the test fluid, a constant temperature oil bath, a temperature regulator, a vacuum pump and gage, and a water condenser.

In the stainless steel tube method, 30 millimeters of a degassed fluid were heated in a cleaned stainless steel (AISI type 321) tube in a purified nitrogen atmosphere at 600°F for 10 hours. Changes in viscosity and neutralization number were measured. The test was repeated with fresh fluid both at 650°F and 700°F, or until an appreciable change in fluid properties was observed.

Tube dimensions were 3/4-inch OD by 10 inches long. A pure nickel Voi-Shan seal was inserted on the plug prior to closing. The threads on the B-nuts and plugs were taped with H-film* to prevent seizure of the threaded surfaces.

The results of these tests on MLO 60-294, HTHF 6294, MCS-310, MCS-3101, PR-143AB, MCS-293, F-50, and XRM-154D are tabulated in Table 2. PR-143AB showed the best stability at all test temperatures, with MCS-293 a close second. In third place, MLO 60-294 showed slightly better stability than fourth place XRM-154D. MCS-3101 and F-50 were marginal at 600°F or above because of their high acid numbers. MCS-310 showed better stability than MCS-3101 as indicated in Table 3. A continuous stream of bubbles, which was tested and found to be acidic, emanated from MCS-3101 fluid for several hours after cooling to room temperature. F-50 fluid that was transferred from the thermal stability tube to a

* DuPont trademark

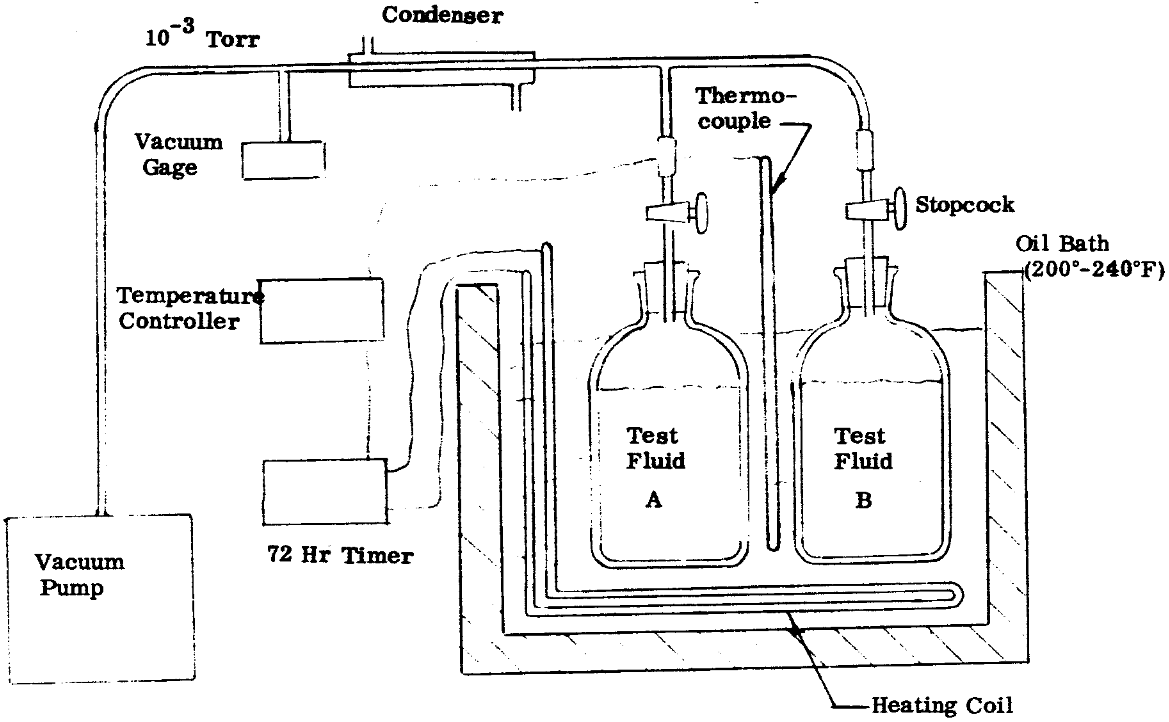

Figure 1. Schematic of Fluid Degassification System

TABLE 2. THERMAL STABILITY OF FLUIDS

(30 ml of degassed fluid heated in a stainless steel tube under cover of purified nitrogen)

		MLO 60-294	HTHF 6294	MCS-3101	MCS-293	F-50	XRM-154D	PR-143AB
Fresh Fluid	Appearance of fluid	Clear with light yellow tint	Clear with light yellow tint	Clear with slight cloudy color	Clear with slight yellow tint	Clear like water	Clear like water	Clear like water
	Viscosity @ 100°F, cs	15.02	15.00	4.34	25.30	48.18	60.68	60.20
	Viscosity @ 210°F, cs	3.26	3.29	1.32	4.18	15.99	17.31	7.94
	Acid No., mg KOH/g	.03	.02	.11	.01	.03	.01	.01
Fluid After 10 hours @ 600°F	Appearance of fluid	Milky white	Clear like water	Very dark brown	Clear with slightly yellower tint	Clear with light yellow	Clear like water	Clear like water
	Viscosity @ 100°F, cs	14.45	14.52	4.37	25.45	45.44	58.85	60.85
	% Viscosity change @ 100°F	-3.8	-3.2	+6.9	+0.6	-5.7	-3.0	+1.1
	Viscosity @ 210°F, cs	3.18	3.22	1.36	4.19	15.66	16.43	7.96
	% Viscosity change @ 210°F	-2.4	-2.1	+3.0	+0.2	-2.0	-5.1	+.2
	Acid No., mg KOH/g	-	.03	.16	-	1.0	.03	.01
Fluid After 10 hours @ 650°F	Appearance of fluid	Milky white	Milky white	Opaque black with continuous foaming	Clear with amber color	Clear with amber color. Vapor cloud over fluid	Clear like water	Clear like water
	Viscosity @ 100°F, cs	12.01	12.30	4.68	25.76	43.94	57.40	60.40
	% Viscosity change @ 100°F	-20	-18	+7.8	+1.8	-8.8	-5.7	+.3
	Viscosity @ 210°F, cs	2.90	2.97	1.50	4.24	15.67	15.98	7.97
	% Viscosity change @ 210°F	-11	-9.7	+13.6	+1.4	-2.0	-7.7	+.4
	Acid No., mg KOH/g	.03	.02	.72	.08	4.29	-	.01
Fluid After 10 hours @ 700°F	Appearance of fluid	Light yellow-brown, transparent, black residue	-	-	Medium brown, translucent	Dark brown opaque	Clear like water with slight haze	Clear like water
	Viscosity @ 100°F, cs	9.3	-	-	27.35	55.72	40.63	60.61
	% Viscosity change @ 100°F	-37.9	-	-	+8.1	+15.6	-33.0	+0.8
	Viscosity @ 210°F, cs	2.55	-	-	4.25	19.36	11.83	8.04
	Acid No., mg KOH/g	.27	-	-	.03	4.41	.03	-

TABLE 3. THERMAL STABILITY OF MCS-310 AND MCS-3101 FLUIDS

Fluids were heat soaked in SS321 tubes

		MCS-310	MCS-3101
Fresh Fluid	Appearance of fluid	Clear like water	Clear with slight haze
	Viscosity @ 100°F, cs	4.22	4.34
	Viscosity @ 210°F, cs	1.35	1.32
	Acid No., mg KOH/g	.04	.11
Fluid After 10 Hrs. @600°F	Appearance of fluid	Opaque black	Very dark brown
	Viscosity @ 100°F, cs	4.28	4.37
	% Viscosity change @ 100°F	+1.4	+.7
	Viscosity @ 210°F, cs	1.37	1.36
	% Viscosity change @ 210°F	+1.5	+3.0
	Acid No., mg KOH/g	.08	0.16
Fluid After 10 Hrs. @ 650°F	Appearance of fluid	Opaque black	Opaque black
	Viscosity @ 100°F, cs	4.40	4.68
	% Viscosity change @ 100°F	+4.3	+7.8
	Viscosity @ 210°F, cs	1.33	1.50
	% Viscosity change @ 210°F	-1.5	+13.6
	Acid No. mg KOH/g	.10	0.72

glass container at room temperature exhibited a vapor cloud over the liquid. F-50 showed a higher acid content than the MCS-3101, although a larger volume of acidic gases evolved from the latter. One possible explanation is that the acidic gases were insoluble in MCS-3101 fluid, while the acidic decomposition products of F-50 remained in solution.

Thermal stability tests were repeated on MCS-310 at 600°F and 650°F and MCS-3101 at 650°F. The samples were sent to Monsanto for analysis. Monsanto's results are compared with the results from Republic's original test run in the following tabulation.

	Republic MCS-310	Monsanto MCS-310	Republic MCS-3101	Monsanto MCS-3101
10 hrs @ 600°F	.08 mg KOH/g	No HX	.16 mg KOH/g	-
10 hrs @ 650°F	.10 mg KOH/g	Strong HX	.72 mg KOH/g	No HX, trace phenol

HX represents hydrogen chloride and/or hydrogen bromide. The discrepancies in these results have not been satisfactorily explained.

Thermal stability tests were rerun on another lot of F-50. A comparison of results of tests on the two lots is as follows:

		New Lot F-50 (lot 473)	Old Lot F-50 (lot 668)
Fresh fluid	Appearance of fluid	clear like water	clear like water
	Acid No., mg KOH/g	.03	.03
Fluid after 10 hours	Appearance of fluid	light amber, transparent	clear, light yellow tint
@ 600°F	Acid No., mg KOH/g	.63	1.0
Fluid after 10 hours	Appearance of fluid	amber, transparent	amber, transparent
@ 650°F	Acid No., mg KOH/g	5.46	4.29
Fluid after 10 hours	Appearance of fluid	opaque, black	opaque, black
@ 700°F	Acid No., mg KOH/g	22.5	4.41

The marked differences observed in the acid numbers of the fluids exposed to 700°F were due possibly to variations between batches of the same nominal fluid formulation.

b. Fire Resistance

Flash and fire point, auto ignition, hot manifold, and high pressure spray ignition data were determined by Republic and/or supplied by the fluid vendors. As can be seen from Tables 4, 5, and 6, the fire resistance of the candidate fluids varied with the test method; however, PR-143AB showed consistently superior fire resistance over the other fluids.

High pressure spray ignition test data, presented in Tables 6A, 6B, and 6C show marked differences in test results. This illustrates the wide variations of results obtained by different investigators. Apparent minor differences in the flammability between MCS-3101 and MLO 60-294 fluids prompted a repeat of the Republic tests in the presence of Monsanto personnel. Monsanto representatives demonstrated their test technique for comparative purposes by showing a movie film of the high pressure spray ignition test. It was mutually agreed that visible differences between results obtained by the two companies may be attributed to variations in flow rates, spray droplet size, intensity of oxyacetylene flame, fluid-to-flame ratio, and air circulation around the spray. In Republic's test setup, the spray mist appeared finer and would have carried only to a distance of six feet had the trough and screen (Figure 2) not been present. The air was quiescent around the spray, in contrast to Monsanto's forced circulation of air. Republic used a hotter flame, while Monsanto used an "equilibrium flame," i.e., equal fuel-to-oxygen ratio. Another noted difference was the lower fluid-to-flame ratio in the test setup at Republic.

Republic's test setup, pictured in Figure 2 includes an accumulator with fluid pressurized to 1000 psi from a nitrogen bottle source. The fluid and gas are separated by a piston barrier. A hand pump was used to feed fluid into the accumulator. A square edged hole of .015 inch diameter was made in a brass insert which threads into the hand valve. A trough, 33 inches long by 8 inches wide and 2 inches deep, with a 30-mesh screen at a distance of 30 inches from the orifice was attached to the unit to permit indoor use.

TABLE 4. FLAMMABILITY OF FLUIDS

Fluid	Flash Point °F	Fire Point °F	Autogenous Ignition Temperature °F
XF-1-0294	430	500	850
XF-1-0291	560	snuffing	900
XRM-154D	525	615	795
MCS-293	445	540	940
F-50	585	680	~ 900
MLO 60-294	390	425	700
MCS-310	335	535	1185
PR-143AB	-*	-*	> 1300
HTHF 70V	430	475	735
Skydrol 500A	350	440	> 1100
ETO 5251	520	-	824
F-560	550	660	900
MIL-H-5606	190	205	475
MLO-7277	440	495	735
OS-124	550	660	1135
Silphenylenes	625	690	900
HTHF 8515	390	450	760

* No flash or ignition reported.

TABLE 5. HOT MANIFOLD TEST, AMS-3150C

	Manifold Temperature, °F			
Fluid	1100	1165	1215*	1240*
MLO 60-294	Drops roll off tube to rim. Slight flame on rim. No smoke	Flames on rim	Fluid bursts into large flames immediately on contact with tube. Flaming drops drip off rim.	Fluid bursts into large flames immediately on contact with tube. Flaming drops drip off rim.
HTHF 6294	Same as MLO 60-294	Same as MLO 60-294	Same as MLO 60-294	Same as MLO 60-294
HTHF 70V	Ignites shortly after contact on tube. Slight smoke.	Fluid burns more readily on tube.	Fluid bursts into flames. Flaming drops drip off rim.	Fluid bursts into flames. Flaming drops drip off rim.
XRM-154D	Drops roll off tube to rim. Flashes on rim.	Flames on rim.	Fluid bursts into flames. Flaming drops drip off rim.	Fluid bursts into flames. Flaming drops drip off rim.
F-50	Drops roll off tube to rim. Flashes on rim	Flames on rim.	Fluid bursts into flames with heavy soot given off and white deposit on tube.	Fluid bursts into flames with heavy soot given off and white deposit on tube.
MCS-293	Drops roll off tube to rim. Slight smoke.	Flashes on rim.	Smokes, then flashes.	Smokes, then flashes.
MCS-3101	Smokes, no flame.	Smokes, no flame.	Smokes, no flame.	Smokes, no flame.
PR-143 AB	Vaporizes.	Smokes slightly.	Smokes, no flame.	Smokes, no flame.

* No flame in pan observed with any of the fluids tested.

TABLE 6A. HIGH PRESSURE SPRAY IGNITION TEST, AMS 3150C
(Vendors' Data)

MCS-310	Fluid did not flash or ignite up to 8 feet from the orifice
MCS-293	Fluid ignited at 18 inches from orifice
PR-143AB	No flash or fire
F-50	Flashes with difficulty at 1 foot from orifice
MLO 60-294	Flashes at 6 inches from orifice

TABLE 6B. HIGH PRESSURE SPRAY IGNITION TEST, MIL-F-7100
(Republic Data)

MCS-3101	Fluid ignited 1 to 2 inches from orifice
MLO 60-294	Fluid ignited 2 to 3 inches from orifice
F-50	Fluid ignited 12 to 13 inches from orifice
PR-143AB	No flash or fire up to 2 feet
MCS-293	No flash or fire up to 2 feet

TABLE 6C. HIGH PRESSURE SPRAY IGNITION TEST, AMS3150C
(Monsanto Data)

MCS-310	Does not ignite or flash up to 8 feet from orifice
Superrefined hydrocarbon	Burns 4 to 8 inches from orifice; flame self-sustaining and carries to target
Chlorine-containing silicone	Burns 8 to 16 inches from orifice; flame self-sustaining
Skydrol 500 A	Burns 3 to 4 feet from orifice; flame self-extinguishing
MCS-293	Burns 1 to 2 feet from orifice; flame carries downstream
Ester engine oil	Burns 4 to 8 inches from orifice; flame self-sustaining and carries to target
High temperature silicate ester	Burns 4 to 8 inches from orifice; flame self-sustaining and carries to target

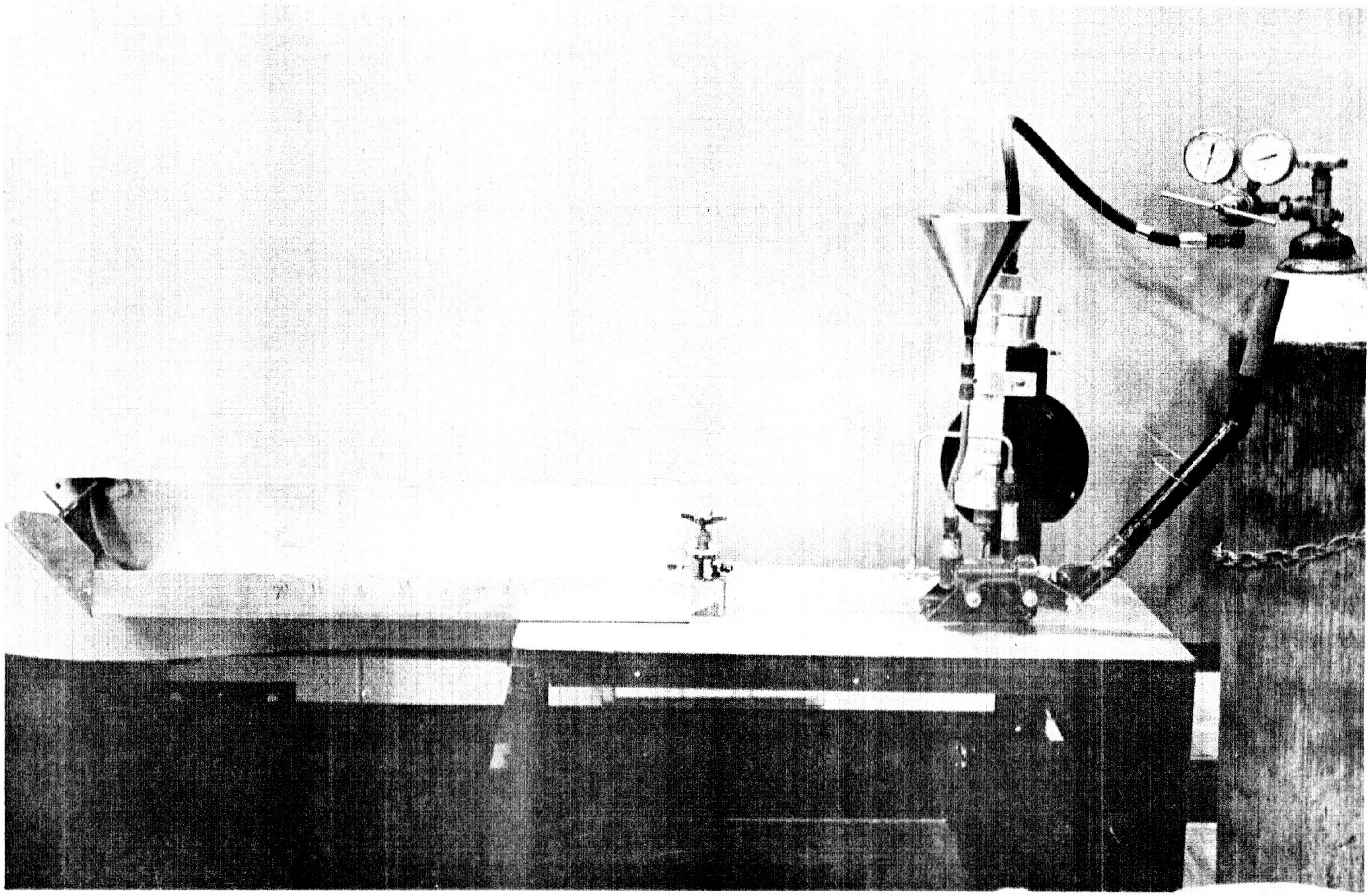

Figure 2. High Pressure Spray Ignition Test Setup

c. Viscosity

Cannon-Fenske and Ubbelohde viscometers were used. Viscosities of fresh fluids determined at Republic and by the fluid manufacturers are contained in Table 7 and Figure 3. The following fluids have suitable viscosities (3600 cs or below) at -40°F: F-50, XF-1-0291, XRM-154D, MLO 60-294, and MCS-310. PR-143AB and MCS-293 reach 3600 cs at 0°F and +10°F, respectively. Fluids that meet the target viscosity requirements of 3600 cs at -40°F and 1 cs at 600°F are XF-1-0291, F-50, and XRM-154D.

d. Bulk Modulus

Bulk modulus data received from the various fluid manufacturers are tabulated in Table 8 and plotted in Figures 4 to 12. The ratings of each fluid, in order of decreasing bulk modulus, appear to be as follows: MCS-293, MCS-310, MLO 60-294, F-50, XF-1-0291, and PR-143AB. Insufficient data on MCS-310 and MCS-293 is presently available to clearly define the bulk modulus properties of these fluids under the various temperature and pressure conditions. However, in order to make a comparison among the fluids, it was assumed that the slopes of the pressure curves at constant temperature are approximately the same for most fluids. Therefore, if a single bulk modulus value is known, a line drawn through the point of proper slope may be used to extrapolate the bulk modulus values at other pressures. It should also be noted that bulk modulus values obtained by the adiabetic method are inherently higher than those obtained by the isothermal secant method.

e. Vapor Pressure

Vapor pressures of some fluids were determinable with the differential thermal analysis apparatus by measuring the boiling point as a function of changing pressure. The Clausius-Clapeyron equation:

$$\ln p = - \frac{\Delta H_v}{RT} + C$$

where

p = vapor pressure

ΔH_v = heat of vaporization

TABLE 7. VISCOSITY OF FLUIDS

Lot No.	Fluid	Source of Data	Viscosity, cs -65°F	-40°F	-20°F	0°F	100°F	210°F	300°F	400°F	500°F	600°F
-	F-50	General Electric	2500				52	16		4.5		2.3
668	F-50	RAC, degassed fluid					48.18	15.99				
473	F-50	RAC, degassed fluid							8.96	5.05		
-	MCS-310	Monsanto		3650.0	353.0	82.7	4.20	1.32	.61 @ 365°F	.465 @ 435°F		
W-1a	MCS-3101	RAC, degassed fluid					4.34	1.32	.81	.52		
-	MCS-293	Monsanto				13040	25.2	4.13	2.0		.81	.48 @ 700°F
QD35	MCS-293	RAC, degassed fluid					25.30	4.18	1.96	1.13		
-	MLO-60-294	Humble	26,048	3644		360.9	15.08	3.30			.61 @550°F	
none	MLO-60-294	RAC, degassed fluid					15.02	3.26	1.62	.96		
4	PR-143AB	DuPont			20,196 @ -25°F	3635	59.6	7.95		1.47		
4	PR-143AB	RAC, degassed fluid					62.75	8.28	3.03	1.43		
-	6294	Oronite	39,306	3672		335.6	14.62	3.21			.57 @550°F	
18.207	6294	RAC, degassed fluid					15.00	3.29				
-	XRM-154D	Socony Mobil	9000	2480			58.78	16.46		4.9	2.8 @550°F	
none	XRM-154D	RAC, degassed fluid					60.68	17.31				
-	XF-1-0291	Dow Corning		1670		400	97	33		10	6.5	
-	XF-1-0294	Dow Corning		12,400		103 @77°F	62.4	12.4				

TABLE 8. BULK MODULUS VALUES OF FLUIDS

MLO 60-294 — Adiabatic Method (Esso Research)

Pressure psig	Bulk Modulus, psi	Pressure, psig	Bulk Modulus, psi
0°F		500°F	
0	353,000	0	59,500
1,000	365,000	1,000	72,600
2,000	378,000	2,000	83,400
3,000	388,000	3,000	95,300
4,000	403,000	4,000	106,000
5,000	416,000	5,000	118,000
100°F		600°F	
0	266,000	0	34,000
1,000	280,000	1,000	45,800
2,000	292,000	2,000	57,300
3,000	304,000	3,000	68,600
4,000	320,000	4,000	78,800
5,000	333,000	5,000	87,600
200°F			
0	198,000		
1,000	212,000		
2,000	224,000		
3,000	238,000		
4,000	251,000		
5,000	263,000		
300°F			
0	141,000		
1,000	152,000		
2,000	163,000		
3,000	179,000		
4,000	189,000		
5,000	200,000		
400°F			
0	93,800		
1,000	107,000		
2,000	118,000		
3,000	131,000		
4,000	141,000		
5,000	154,000		

Esso Research

F-50 — Adiabatic Method (General Electric)

Pressure, psia	Bulk Modulus, psi
100°F	
100	140,000
1,000	156,000
2,000	173,000
3,000	184,000
4,000	190,000
5,000	194,000
6,000	198,000
250°F	
100	88,000
1,000	105,000
2,000	120,000
3,000	130,000
4,000	139,000
5,000	148,000
6,000	156,000
400°F	
100	54,000
1,000	67,000
2,000	81,000
3,000	93,000
4,000	103,000
5,000	113,000
6,000	124,000
600°F	
100	24,000
1,000	34,000
2,000	46,000
3,000	56,000
4,000	67,000
5,000	76,000
6,000	85,000

General Electric

PR-143AB — Isothermal Secant (DuPont)

Pressure, psig	Bulk Modulus, psi
70°F	
1,000	138,600
3,000	150,500
5,000	162,200
100°F	
1,000	125,000
3,000	137,000
5,000	149,000
210°F	
1,000	82,300
3,000	94,000
5,000	106,000
335°F	
1,000	48,800
3,000	60,500
5,000	72,300
425°F	
1,000	32,000
3,000	43,700
5,000	55,500

DuPont

MCS-293 — Isothermal Secant (Monsanto)

Temp., °F	Bulk Modulus, psi
0-7500 psi	
0	500,000
77	410,000
100	340,000
210	285,000
300	230,000
500	190,000

MCS-310 — Isothermal Secant

Temp., °F	Bulk Modulus psi
0-7000 psi	
77	365,000
200	287,000
300	229,000
400	180,000

Monsanto

XF-1-0291 — Isothermal Secant (Dow Corning)

Temp., °F	Bulk Modulus, psi
0-4000 psi	
77	170,000
400	77,000
500	57,000
Isothermal Tangent 4000 psi	
77	215,000
400	110,000
500	89,000

XF-1-0294 — Isothermal Secant

Temp., °F	Bulk Modulus, psi
0-4000 psi	
77	190,000
400	86,000
500	64,000
Isothermal Tangent 4000 psi	
77	230,000
400	117,000
500	95,000

Dow Corning

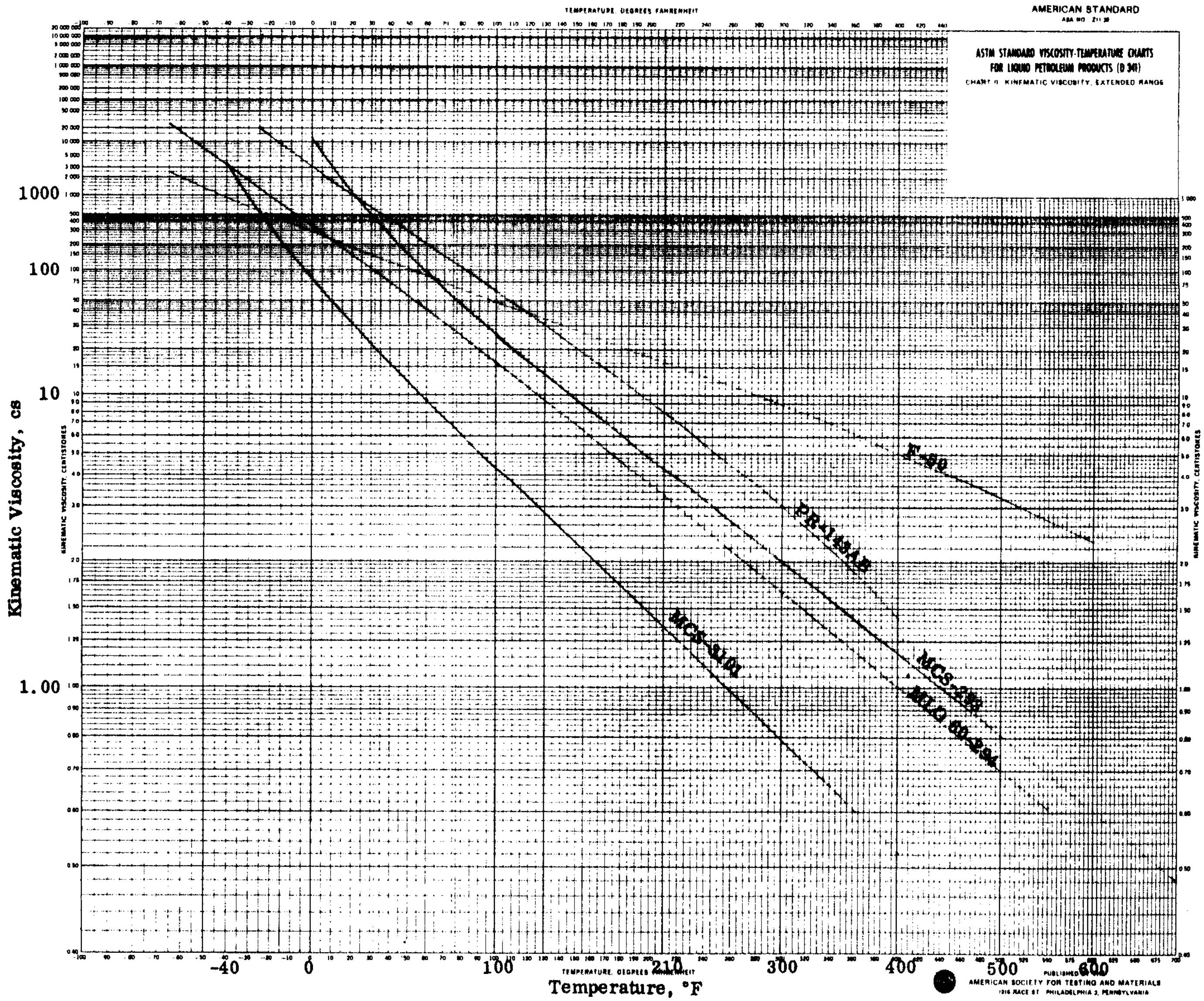

Figure 3. Viscosity-Temperature Curves

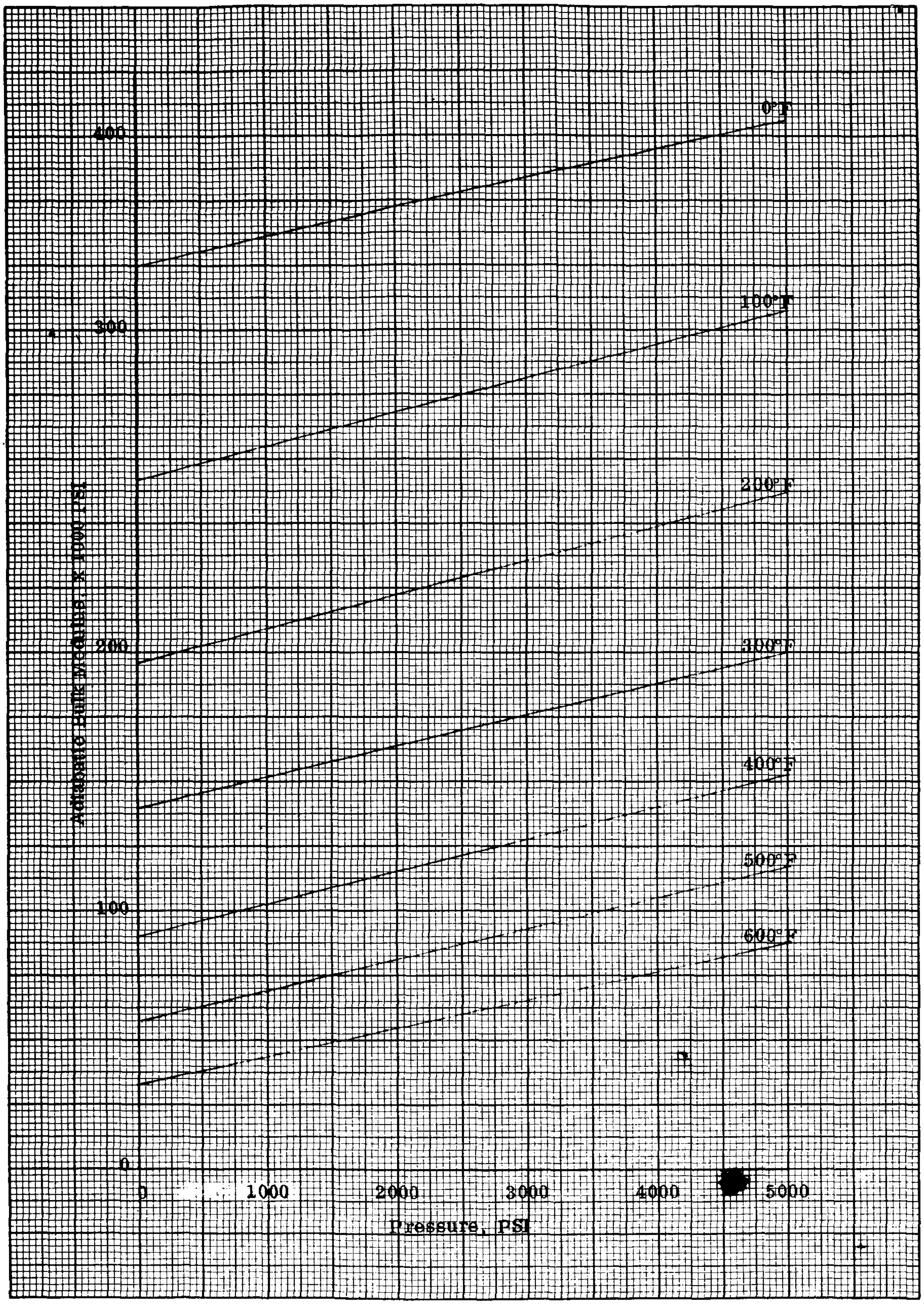

Figure 4. Adiabatic Bulk Modulus of MLO 60-294 Fluid

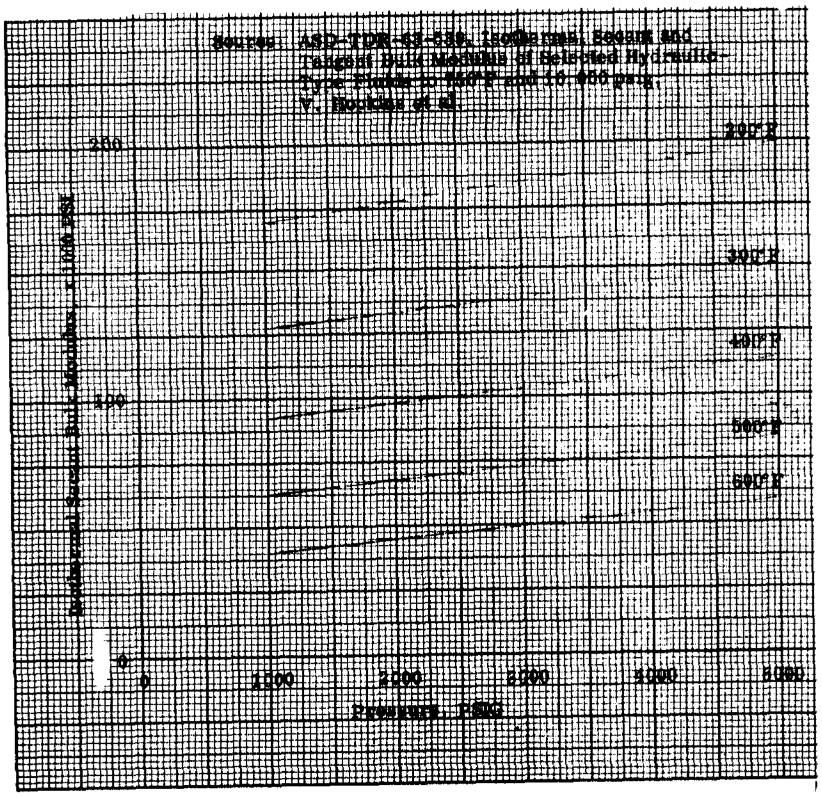

Figure 5. Isothermal Secant Bulk Modulus of MLO 60-294 Fluid

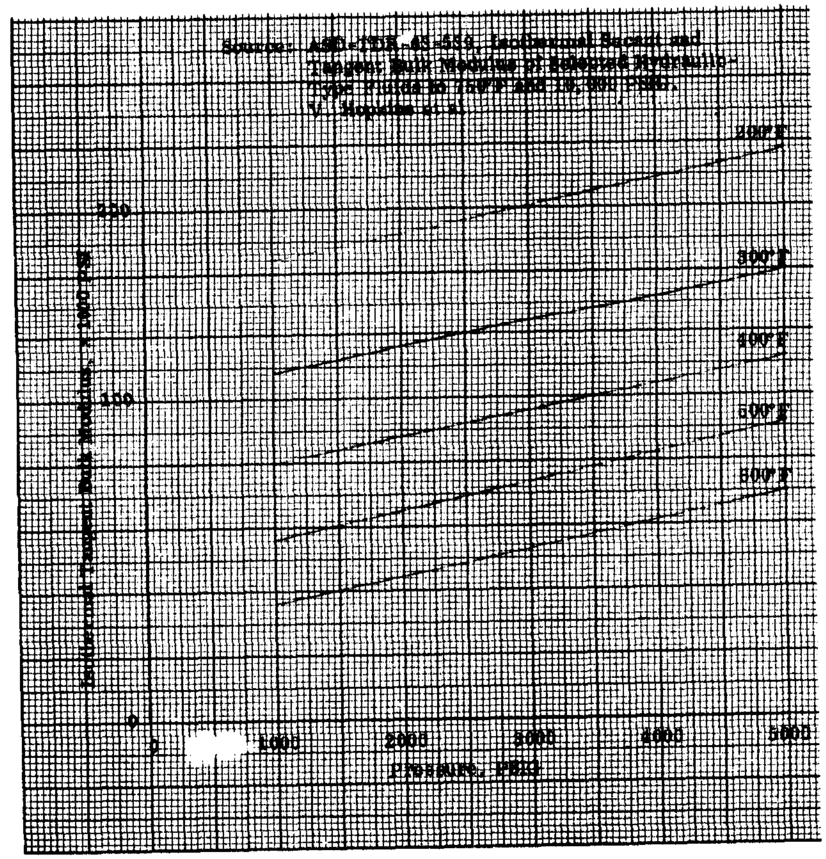

Figure 6. Isothermal Tangent Bulk Modulus of MLO 60-294 Fluid

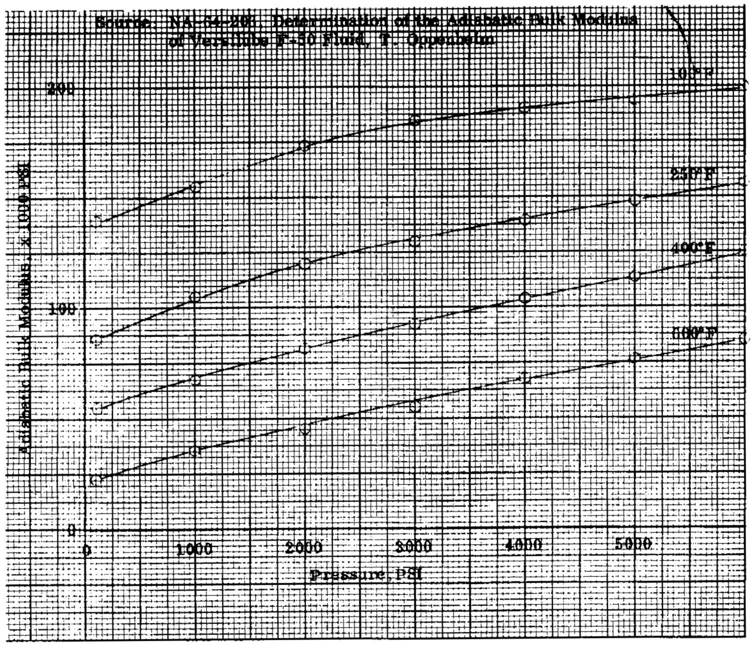

Figure 7. Adiabatic Bulk Modulus of F-50 Fluid

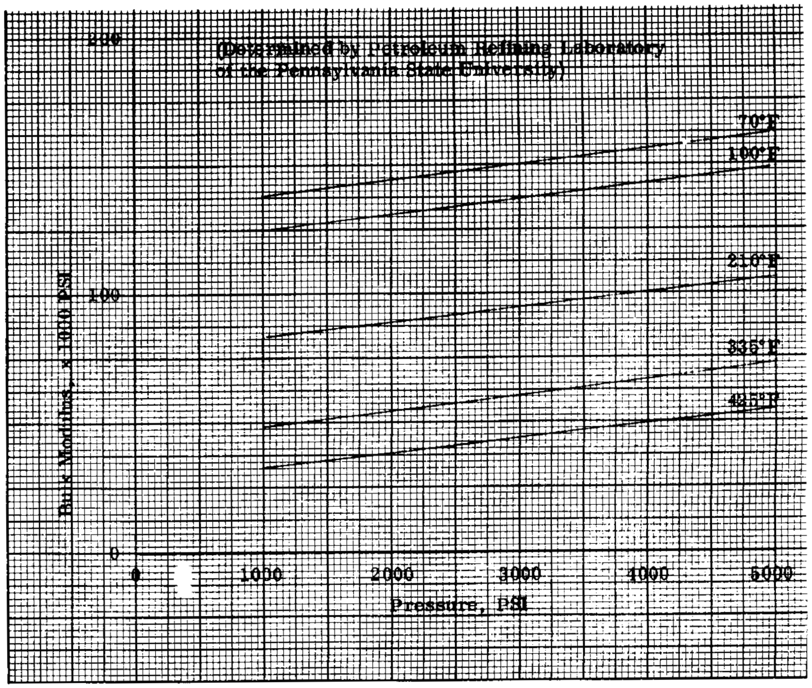

Figure 8. Isothermal Secant Bulk Modulus of PR-143 Hydraulic Oil

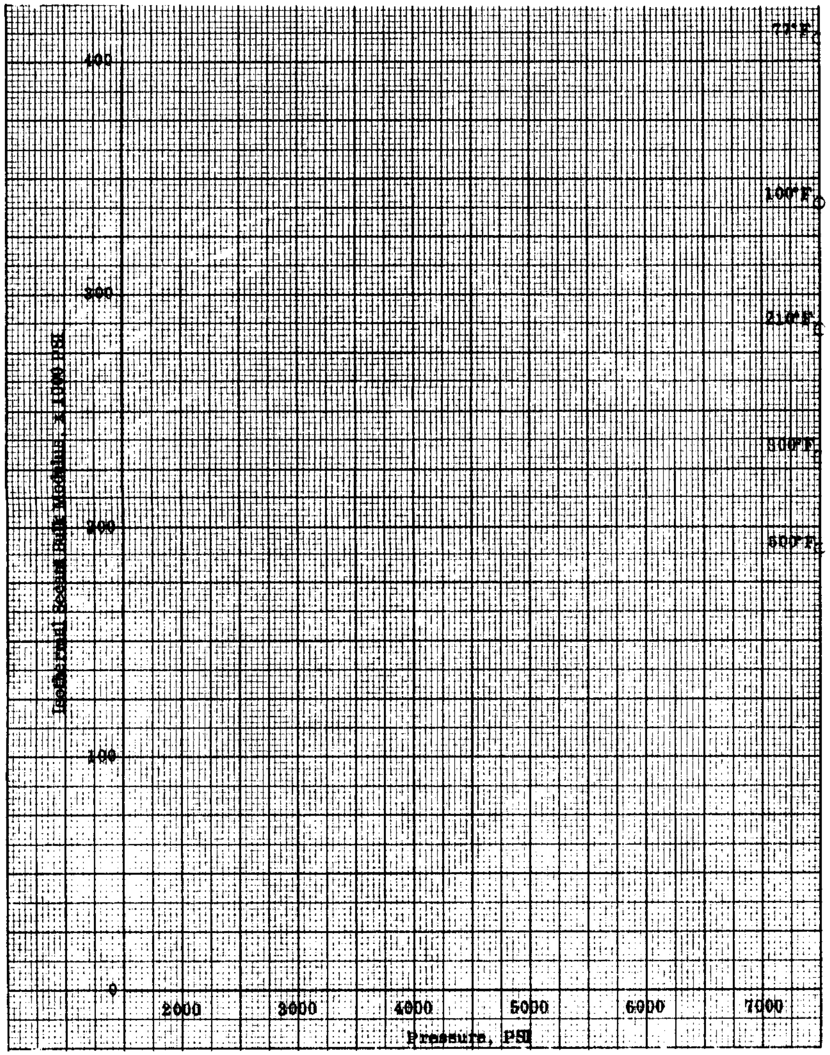

Figure 9. Isothermal Secant Bulk Modulus of MCS-293 Fluid

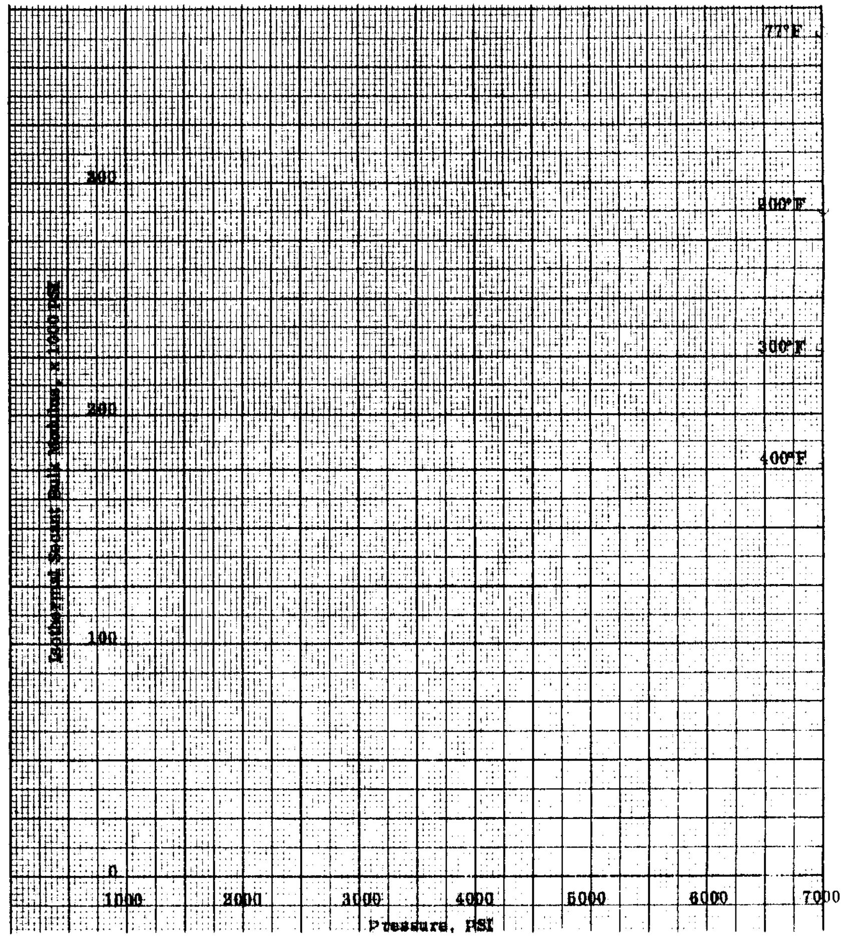

Figure 10. Isothermal Secant Bulk Modulus of MCS-310 Fluid

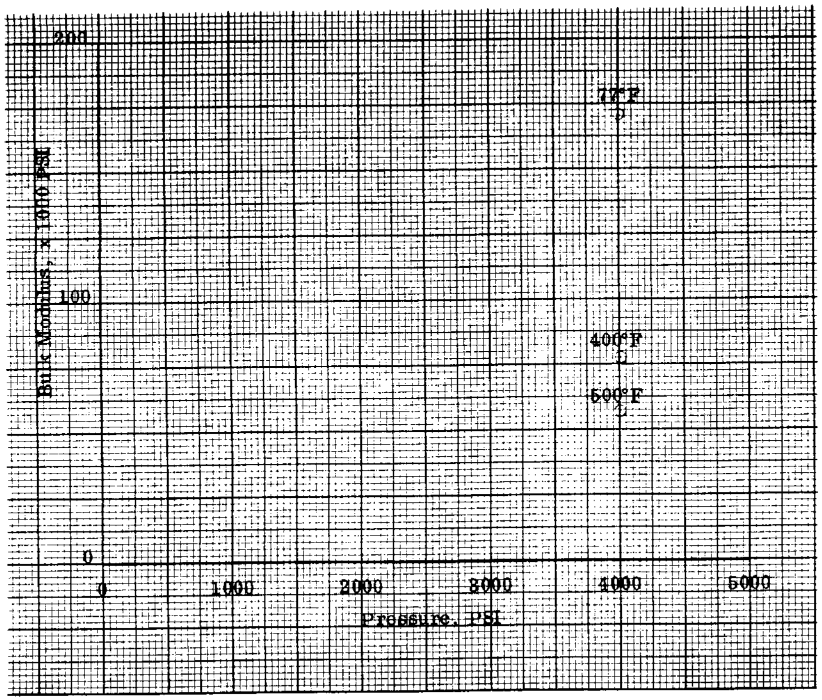

Figure 11. Isothermal Secant Bulk Modulus of XF-1-0291 Fluid

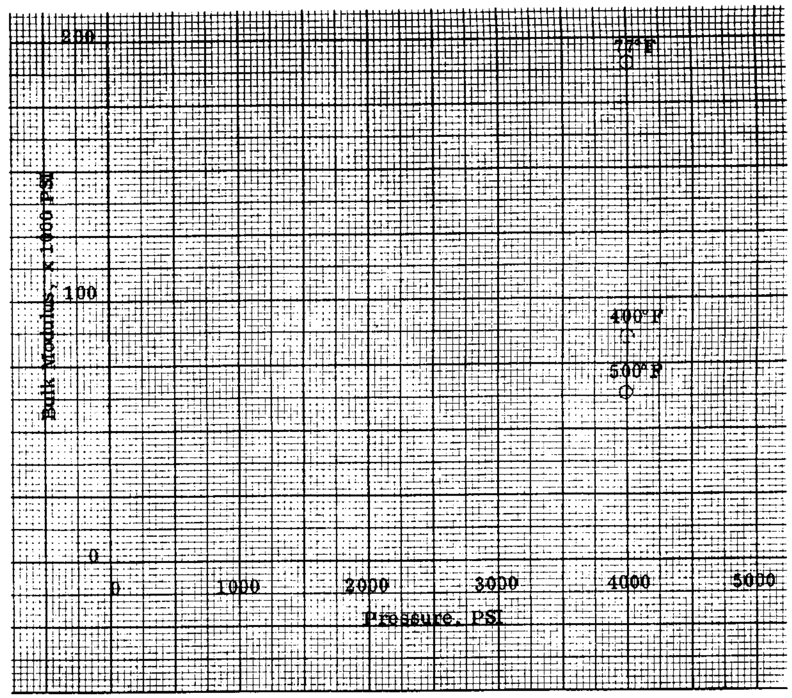

Figure 12. Isothermal Secant Bulk Modulus of XF-1-0294 Fluid

R	=	gas constant
T	=	temperature
C	=	constant related to entropy of the transition

may be used to express this reversible volatilization process. Some assumptions made in deriving the equation are (1) the volume of the vapor is much greater than the volume of the condensed phase, (2) the vapor obeys the ideal gas law, and (3) ΔH_v is constant over the temperature interval under consideration.

The test method was not suitable to the vapor pressure measurement of F-50 silicone oil and PR-143AB fluorocarbon fluid. The latter fluids, probably a blend of polymers of closely varying molecular weight, produced a gradual change in boiling points without significant peak temperature.

The DTA apparatus used in these experiments is DuPont's Model 900. Two glass capillaries were filled with minute glass beads, each to a height of 3/16 of an inch. To one capillary, three microliters of the test fluid were introduced with a syringe. Thermocouples were inserted in both capillaries. The apparatus was evacuated to about 10 Torr and heated at a rate of 20°C per minute.

The vapor pressure data obtained for MCS-293, MCS-3101, and MLO 60-294 fluids by the DTA method are shown in Table 9 and Figures 13 and 14. Vapor pressure data on MCS-293 fluid, Figure 13, were limited because of the corrosive attack by the fluid on the immersed thermocouple.

Vendor-supplied data on vapor pressure, obtained by isoteniscope, are also included in Table 9. A comparison of the data by the two methods is shown in Figure 13.

f. Density and Coefficient of Expansion

Fluid manufacturers' data on fluid density and coefficient of expansion are tabulated in Table 10.

TABLE 9. VAPOR PRESSURE OF SELECTED FLUIDS

DTA Method*						Isoteniscope Method**															
MLO 60-294		MCS-3101		MCS-293		MLO 60-294		PR-143AB		F-50		MCS-310		MCS-293		XRM-154D		XF-1-0291		XF-1-0294	
Torr	°F	Torr	°F	Torr	°F	Torr	°F	Torr	°F	Torr	°F	Torr	°F	Torr	°F	Torr	°F	Torr	°F	Torr	°F
20	477	13	363	20	576	.01	200	1.7	350	.1	125	20	367	140	700	.05	100			1.3	356
55	547	23	387	35	622	.06	250	5	400	1.2	300	40	410	760	795	.14	150	.7	400	1.95	370
121	586	60	432	104	700	.38	300	13	450	4.3	450	100	460			.36	200	7.6	500	2.9	392
241	633	168	493			1.7	350	34	500	8.5	600	140	488			.65	250	25.0	550	4.2	406
764	736	766	608			6.0	400	74	550	700	680	760	615			.99	300	64.0	600	5.6	424
						17	450	270	650							1.54	350	170.0	650	7.8	442
						50	500	470	700							2.20	400	(Estimated)		12	464
																3.30	450			16	487
																4.84	500			23	509
																				32.5	529
																				(Read from graph)	

* RAC data
** Vendor data

TABLE 10. DENSITY AND COEFFICIENT OF EXPANSION OF SEVERAL FLUIDS

F-50		MLO 60-294		PR-143AB		MCS-310		MCS-293		XF-1-0291		XF-1-0294	
Density g/ml	Temp. °F	Density g/ml	Temp. °F	Density g/ml	Temp. °F	Density g/ml	Temp. °F	Density g/ml	Temp. °F	Density g/ml	Temp. °F	Density g/ml	Temp. °F
1.0265	100	.8318	100	1.8815	75	1.445	0	1.195	77	1.064	77	1.286	-40
.9554	250	.7919	210	1.8017	150	1.406	73	1.184	100	1.053	100	1.262	0
.8843	400	.6666	546	1.7473	210	1.392	100	1.101	300	.997	210	1.217	77
.7865	600					1.383	126	1.017	500	.904	400	1.129	230
						1.335	210	.926	700			1.031	400
						1.285	300						
						1.226	400						
Coefficient of Expansion													
.00048 per °F (100-600°F)		.00037 per °F (100-546°F)		.00099 per °F (75-210°F)		.00041 per °F (0-400°F)		.00043 per °F (77-700°F)		.000551 per °F (77°F to 400°F)		.0005637 per °F (-40°F to 400°F)	

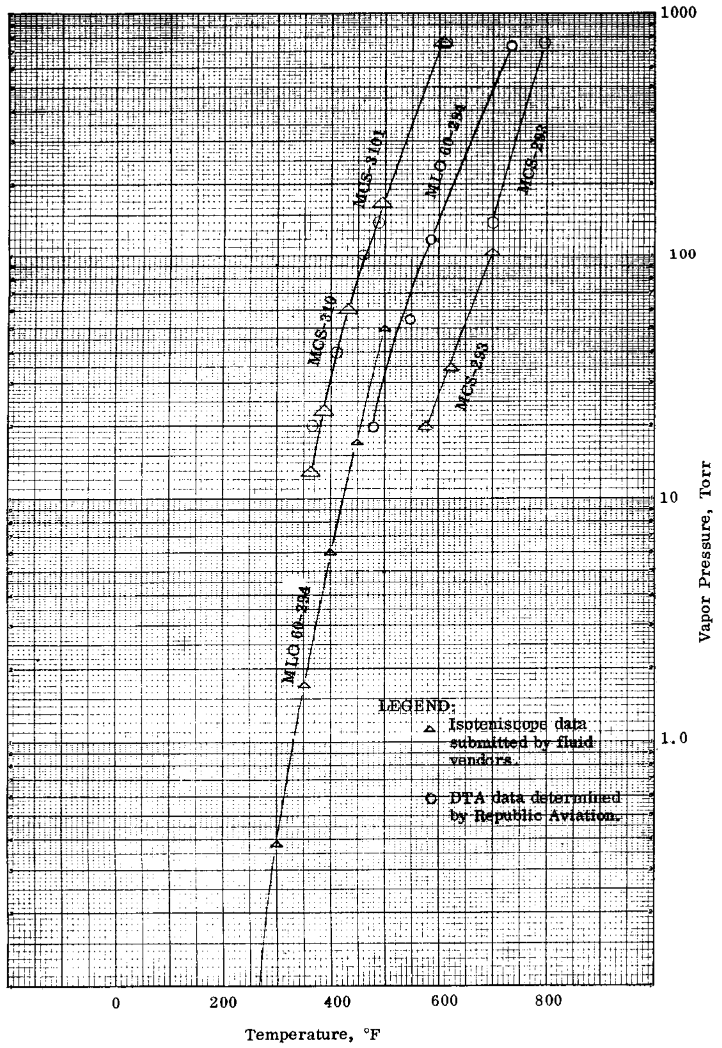

Figure 13. Vapor Pressure Curves of MCS-310, MCS-3101, MCS-293 and MLO 60-294 Fluids

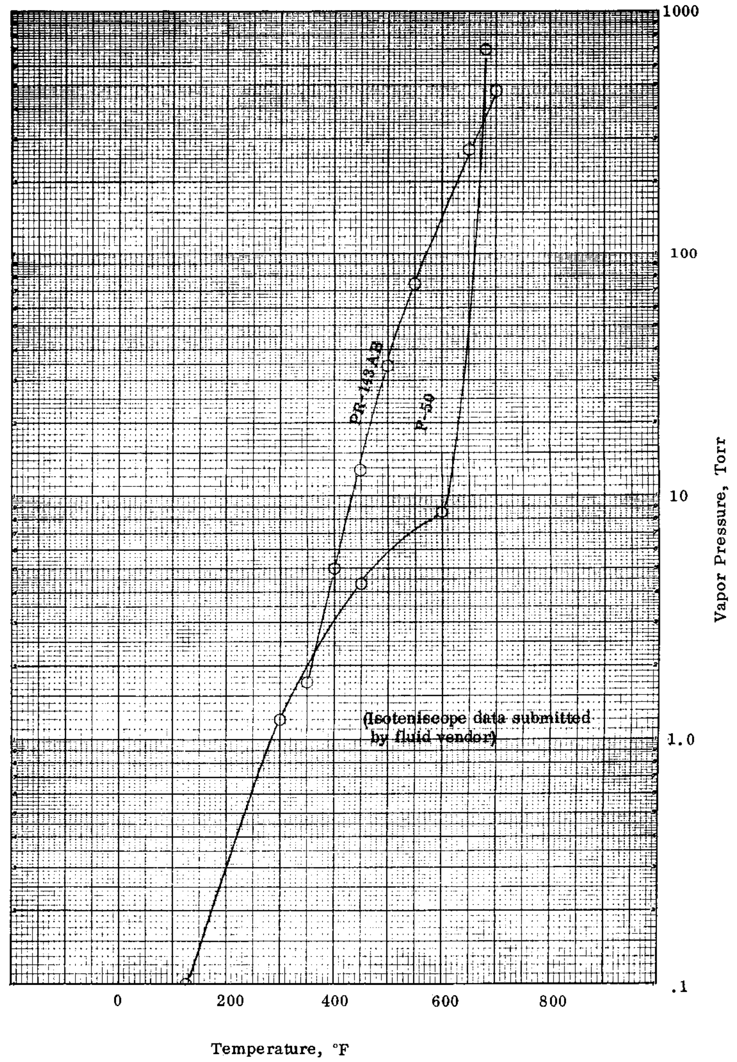

Figure 14. Vapor Pressure Curves of PR-143 and F-50 Fluids by the Isoteniscope Method

g. Materials Compatibility

The candidate fluids were investigated for their effect on hydraulic system and other aircraft materials, including pump and bearing materials. Results are listed in Tables 11 to 15. Each metal corrosion specimen was heated in degassed fluid under cover of nitrogen gas for 72 hours at 600°F. The tubes and the filling procedure were similar to those used in the thermal stability determinations. Appearances of the corrosion specimens after testing are shown in Figures 15 to 19. Weight losses were converted to equivalent thickness losses, assuming uniform surface corrosion, and are listed in Table 16. MLO 60-294 showed the best compatibility with the materials tested, followed by MCS-293, PR-143AB, F-50, and MCS-3101.

The beneficial effect of heat treatment on corrosion of some materials has been previously observed by others (Reference 10), and shown in Table 18, in connection with PR-143 fluid. This phenomenon varies with the materials and test conditions. The heat treatment of some materials seems to have a similar effect in corrosion tests with MCS-3101. Other fluids indicated a lesser effect (or none) of heat treatment on corrosion rates of materials.

Inasmuch as the compositions of AISI 440C and AISI 440C modified (+4% molybdenum) are similar, it is expected that the corrosion characteristics would also be similar. Consequently, the proposed use of AISI 440C modified as a bearing material for use with MCS-3101 fluid at 600°F is questionable.

Other material specimens such as copper, cadmium, and aluminum were tested although they are not normally considered as airborne high temperature system materials. Cadmium was compatible only with MLO 60-294. Copper was compatible with MLO 60-294, F-50, and PR-143AB. Aluminum was compatible with all fluids except MCS-3101.

MCS-3101 fluid samples recovered from some of the compatibility tests were sent to the supplier for analysis (see Table 17). The AISI 321 stainless steel tube used to heat MCS-3101 and AISI-321 specimen was also analyzed by the fluid vendor. Incipient halide attack at the bottom two-thirds of the tube was indicated. There was no evidence of halide attack at the top third.

TABLE 11. MATERIALS COMPATIBILITY TEST #1

(20 ml of fluid heated to 600°F for 72 hours in the presence of a metal and with nitrogen gas covering the fluid)

		PR-143AB	MLO60-294	MCS-293	MCS-3101	F-50
K-82 Carbide	Weight change, mg/cm^2	+.16	+.20	+.24	-1.96	-.26
	Appearance of specimen	darkened	faint violet-	slightly darkened surface	darkened surface, flaky coating of baked oil	
	Viscosity @ 100°F, cs	60.60	12.71	25.95	-	37.62
	Viscosity @ 210°F, cs	8.07	2.91	4.25	-	15.56
	Acid No., mg KOH/g		.22	.20	1.9	1.8
	Appearance of fluid	clear like water	light yellow	pale yellow, transparent	opaque black acid fumes, odor, some sediment	pale yellow, transparent
K-96 Carbide	Weight change, mg/cm^2	+.16	+.18	+.24	-.06	-.16
	Appearance of specimen	darkened surface	faint violet and green surface	faint rainbow coloring	darkened surface, flaky coating of baked oil	
	Viscosity @ 100°F, cs	60.14	13.10	26.16	-	48.00
	Viscosity @ 210°F, cs	8.11	3.00	4.23	-	15.01
	Acid No., mg KOH/g		.22	.20	1.0	2.1
	Appearance of fluid	clear like water	light yellow, slightly cloudy	pale yellow, transparent	opaque black, acid fumes, odor, some sediment	yellow tint, transparent
AMS-4908, Ti-8 mn	Weight change, mg/cm^2	+.41	+.07	+.13	-3.30	+.05
	Appearance of specimen	coking of fluid in spots	rainbow colored	slight staining	darkened surface, flaky coating of baked oil	shiny surface, clean
	Viscosity @ 100°F, cs	60.37	12.79	25.87	-	48.76
	Viscosity @ 210°F, cs	7.88	3.00	4.25	-	15.69
	Acid No., mg KOH/g		.20	.17	3.3	
	Appearance of fluid	clear like water	clear with light yellow tint	pale yellow, transparent	opaque black, acidic fumes, odor, some sediment	pale yellow, transparent
SS321	Weight change, mg/cm^2	+.71	+.33	+.20	-1.57	+.04
	Appearance of specimen	dull surface, coking of fluid in spots	dull surface, clean	dull surface	darkened surface, flaky coating of baked oil	
	Viscosity @ 100°F, cs	60.06	12.68	25.60	-	51.40
	Viscosity @ 210°F, CS	8.11	2.87	4.25	-	16.25
	Acid No., mg KOH/g		.20	.16	2.8	1.9
	Appearance of fluid	water appearance, slightly cloudy	light yellow, slightly cloudy	pale yellow, transparent	opaque black, acidic fumes, odor, some sediment	pale yellow, transparent
AMS-5537B Haynes 25	Weight change, mg/cm^2	+.08	+.14	+.16	-.86	0.0
	Appearance of specimen	dull surface	slight rainbow coloring	dull surface, some staining	darkened surface, flaky coating of baked oil	
	Viscosity @ 100°F, cs	60.43	12.99	25.79	-	56.75
	Viscosity @ 210°F, cs	8.04	2.90	4.26	-	16.64
	Acid No., mg KOH/g		.12	.20	2.1	2.7
	Appearance of fluid	clear like water	light yellow, slightly cloudy	pale yellow, transparent	opaque black acidic fumes, odor, some sediment	yellow tint, transparent
Fresh Fluid	Viscosity @ 100°F, cs	60.13	15.02	25.30	4.34	48.18
	Viscosity @ 210°F, cs	7.94	3.26	4.18	1.32	15.99
	Acid No., mg KOH/g		.02	.01	.11	.03
	Appearance of fluid	clear like water	clear with light yellow tint	pale yellow, transparent	clear with slight cloudy color	clear like water

TABLE 12. MATERIALS COMPATIBILITY TEST #2

(20 ml of fluid heated to 600°F for 72 hours in the presence of a metal and with nitrogen gas covering the fluid)

		PR-143AB	ML060-294	MCS-293	MCS-3101	F-50
17-7 PH	Weight change, mg/cm^2	-.08	+.08	-.25	-1.83	-.23
	Appearance of specimen	dark gray	dull	dull	black spots on gray	brownish-gray
	Viscosity @ 100°F, cs	60.48	12.66	25.97	--	42.68
	Viscosity @ 210°F, cs	8.10	3.02	4.23	--	15.09
	Acid No., mg KOH/g		.14	.24	3.4	1.7
	Appearance of fluid	clear like water	light yellow, slightly cloudy	transparent amber	opaque black, acid fumes, odor, some sediment	transparent amber
Ti-7Al-4 MO	Weight change, mg/cm^2	+.20	+.13	+.35	-9.91	+.02
	Appearance of specimen	black	bluish gray	dull		shiny
	Viscosity @ 100°F, cs	60.48	13.05	25.95	--	43.08
	Viscosity @ 210°F, cs	7.92	2.92	4.25	--	14.56
	Acid No., mg KOH/g		.14	.16	7.1	1.6
	Appearance of fluid	clear like water	light yellow, slightly cloudy	transparent amber	opaque black, acid fumes, odor some sediment	transparent amber
Ti-6Al-4V	Weight change, mg/cm^2	+.26	+.07	+.14	-7.99	0.0
	Appearance of specimen	black	rainbow colored	dull	slightly stained	shiny
	Viscosity @ 100°F, cs	60.39	12.80	25.98	--	44.61
	Viscosity @ 210°F, cs	7.91	2.92	4.25	--	15.57
	Acid No., mg KOH/g		.15	.15	5.5	1.6
	Appearance of fluid	color translucent	light yellow, slightly cloudy	transparent amber	opaque black, acid fumes, odor some sediment	transparent amber
Rene' 41	Weight change, mg/cm^2	-.08	+.08	+.14	-.82	-.08
	Appearance of specimen	dull	dull	dull	dark gray	dull
	Viscosity @ 100°F, cs	60.24	12.92	25.88	--	39.01
	Viscosity @ 210°F, cs	7.89	3.04	4.24	--	13.16
	Acid No., mg KOH/g		.14	.26	2.5	2.6
	Appearance of fluid	colorless translucent	light yellow, slightly cloudy	transparent amber	opaque black, acid fumes, odor some sediment	transparent amber
Inconel x	Weight change, mg/cm^2	-.22	+.08	+.10	-.40	-.24
	Appearance of specimen	dark gray	slight staining	slight staining	dull	gray
	Viscosity @ 100°F, cs	60.52	12.90	25.94	--	50.36
	Viscosity @ 210°F, cs	7.95	3.05	4.26	--	17.75
	Acid No., mg KOH;g		.15	.27	2.1	3.3
	Appearance of fluid	colorless translucent	light yellow, slightly cloudy	transparent amber	opaque, black acid fumes, odor some sediment	transparent amber
Fresh Fluid	Viscosity @ 100°F, cs	60.13	15.02	25.30	4.34	48.18
	Viscosity @ 210°F, cs	7.94	3.26	4.18	1.32	15.99
	Acid No., mg KOH/g		.02	.01	.11	.03
	Appearance of fluid	clear like water	clear with light yellow tint	pale yellow, transparent	clear with faint haze	clearlike water

TABLE 13. MATERIALS COMPATIBILITY TEST #3

(20 ml of fluid heated to 600° F for 72 hours in the presence of a metal and with nitrogen gas covering the fluid)

		PR-143AB	MLO 60-294	MCS-293	MCS-3101	F-50
Dynalloy 600 Bronze	Weight change, mg/cm^2	+.58	+.35	+.21	-99.07	-.35
	Appearance of specimen	copper colored	dull, some coking	coked oil on one side	severely coked and etched copper colored	some staining
	Appearance of fluid	colorless, transparent	light yellow, slight haze	light amber, slight haze	opaque black, acid fumes, odor, some sediment	amber, shade darker
K-162B Carbide	Weight change, mg/cm^2	+.20	+.16	+.32	-.54	-.54
	Appearance of specimen	dull	like new	slight corrosion	darkened	slight corrosion
	Appearance of fluid	colorless, transparent	pale yellow, slight haze	amber, transparent	opaque black, acid fumes, odor, some sediment	amber, slight haze
AM-350, AMS-5548	Weight change, mg/cm^2	+.02	+.10	+.16	-.87	-.06
	Appearance of specimen	like new	like new	slight staining	dark stained	slight staining
	Appearance of fluid	colorless transparent	faint yellow, slight haze	amber, transparent	opaque black, acid fumes, order, some sediment	amber transparent
Silver Electrolytic	Weight change, mg/cm^2	0.0	+.04	+0.0	+1.51	-.02
	Appearance of specimen	dull	some staining	like new	coked, greenish metal	like new
	Appearance of fluid	colorless, transparent	pale yellow, slight haze	amber, transparent	opaque black, acid fumes, odor, some sediment	amber transparent
Copper QQ-C-576	Weight change, mg/cm^2	-.29	+.16	-3.08	-77.10	-.32
	Appearance of specimen	like new	black staining	coked and etched	severely coked and etched	like new
	Appearance of fluid	colorless, transparent	pale yellow, slight haze	amber, transparent	opaque black acid fumes, odor, some sediment	amber, transparent
Cadmium, QQ-A-671	Weight change, mg/cm^2	-2.65	-.01	-2.57	---	-3.40
	Appearance of specimen	etched, and stained	some pitting	slight etching	flaked apart	flaky surface
	Appearance of fluid	colorless, transparent	light yellow	amber, transparent	opaque black acid fumes, odor, some sediment	amber, transparent
Aluminum, QQ-A-355	Weight change, mg/cm^2	+.09	+.23	+.13	---	-.60
	Appearance of specimen	dull	slight pitting	slight pitting	flaked apart	some etching
	Appearance of fluid	colorless, transparent	light yellow	amber, transparent	black solids	amber, transparent
Hastelloy X, AMS-5536	Weight change, mg/cm^2	+.01	+.01	+.01	-.08	0.0
	Appearance of specimen	like new	like new	dull	like new	like new
	Appearance of fluid	colorless transparent	light yellow	amber, transparent	opaque black, acid fumes, odor, some sediment	amber, transparent
Fresh fluid	Appearance of fluid	clear like water	clear with light yellow tint	pale yellow, transparent	clear with faint haze	clearlike water

TABLE 14. MATERIALS COMPATIBILITY TEST #4

(20 ml of fluid heated to 600° F for 72 hours in the presence of a metal and with nitrogen gas covering the fluid)

		PR-143AB	MLO 60-294	MCS-293	MCS-3101	F-50
AISI-440C, Annealed	Weight change, mg/cm^2	-6.97	+.04	+.09	-5.35	-.18
	Appearance of specimen	scaly coating	tarnished	slight tarnish	powdery substance on surface	brown coating
	Appearance of fluid	colorless, transparent	light yellow, transparent	amber, transparent	opaque black, acid fumes, odor, some sediment	opaque black
AISI-440C, hardened	Weight change, mg/cm^2	0.0	+.07	+.15	-3.39	-.31
	Appearance of specimen	dull	dull	slight tarnish	dart tarnish	brown coating
	Appearance of fluid	colorless, transparent	light yellow, transparent	amber, transparent	opaque black, acid fumes, odor, some sediment	black almost opaque
Hastelloy C, hardened	Weight change, mg/cm^2	+.15	+.15	+.15	0.0	+.07
	Appearance of specimenk	shiny	shiny, green and red tint	spotty corrosion	shiny	shiny
	Appearance of fluid	colorless, transparent	light yellow, transparent	amber, transparent	opaque black, acid fumes odor, some sediment	opaque black
AISI-M2 tool steel annealed	Weight change, mg/cm^2	-5.82	+.13	+.19	-3.78	-.30
	Appearance of specimen	black coating on surface	spotty corrosion, green and red tint,	dull	dark tarnish	black coating
	Appearance of fluid	colorless, transparent	light yellow, transparent	amber transparent	opaque black, acid fumes, odor, some sediment	opaque black
S Monel, QQ-N-288, Comp. D	Weight change, mg/cm^2	-.09	-.03	+.12	-.89	-.10
	Appearance of specimen	dark tarnish	tarnish	dark tarnish	etched	spotty corrosion
	Appearance of fluid	colorless, transparent	light yellow, transparent	amber, transparent	opaque black, acid fumes, odor, some sediment	opaque black
AISI-347, AMS-5512	Weight change, Mg/cm^2	-.05	+.02	+.14	-.85	-.10
	Appearance of specimen	slight tarnish	shiny	spotty corrosion	slight tarnish	slight tarnish
Fresh fluid	Appearance of fluid	colorless, transparent	light yellow, transparent	amber transparent	opaque black, acid fumes, odor, some sediment	black, almost opaque
A-286, AMS-5525	Weight change, mg/cm^2	+.04	+.04	+.11	-.41	-.06
	Appearance of specimen	dark tarnish	shiny, green and red tint	spotty corrosion	slight tarnish	spotty corrosion
	Appearance of fluid	colorless, transparent	light yellow transparent	amber, transparent	opaque black, acid fumes, odor, some sediment	opaque black

TABLE 15. MATERIALS COMPATIBILITY TEST #5

(20 ml of fluid heated to 600°F for 72 hours in the presence of a metal and with nitrogen gas covering the fluid)

		PR-143AB	MLO 60-294	MCS-293	MCS-3101	F-50
1009 Steel, QQ-S-698	Weight change, mg/cm^2	-.79	-.20	-.28	-3.31	-3.75
	Appearance of specimen	some corrosion	powder on surface, shiny beneath	gray powder on surface	dull	dark, brown coating
	Appearance of fluid	colorless transparent	colorless, transparent	light amber, transparent	opaque black, acid fumes, odor, some sediment	amber, transparent
D-2 Ductile Iron, hardened	Weight change, mg/cm^2	-.24	+.05	-1.44	-5.10	-1.35
	Appearance of specimen	dull	dull	pitted and corroded	pitted and corroded	pitted and corroded
	Appearance of fluid	colorless, transparent	milky white which settles on standing	light amber, transparent	opaque black, acid fumes, odor, some sediment	amber, transparent
Nitralloy G Modified 135 steel	Weight change, mg/cm^2	-.46	+.03	+.05	-4.86	-1.94
	Appearance of specimen	spotty corrosion	dull	dull	black powder on surface	powder on surface, corroded
	Appearance of fluid	colorless, transparent	milky white which settles on standing	light amber, transparent	opaque black acid fumes, odor, some sediment	amber, transparent
M-10 Hardened	Weight change, mg/cm^2	-1.57	-.08	-.63	-12.20	-1.89
	Appearance of specimen	spotty corrosion	shiny bronze color	dull	black scaly coating	black scaly coating
	Appearance of fluid	colorless, transparent	milky white which settles on standing	light amber, transparent	opaque black, acid fumes, odor, some sediment	amber, slight haze
M-50 Hardened	Weight change, mg/cm^2	+1.56	-.06	-.62	- 4.37	-3.44
	Appearance of specimen	spotty corrosion	shiny bronze color	spotty corrosion	black scaly coating	black scaly coating
	Appearance of fluid	colorless, transparent	milky white which settles on standing	light amber transparent	opaque black, acid fumes, odor, some sediment	amber, transparent
Hastelloy D Hardened	Weight change, mg/cm^2	-.39	+.16	-.55	-3.07	-.16
	Appearance of specimen	dull	dull	dull	dull	dull
	Appearance of fluid	colorless, transparent	milky white which settles on standing	light amber, transparent	opaque black acid fumes, odor, some sediment	amber, transparent
NM-100 Annealed	Weight change, mg/cm^2	-3.98	+.11	-.24	-7.38	-5.58
	Appearance of specimen	severe pitting	green and red tint	dull	dark coating	spotty corrosion
	Appearance of fluid	colorless, transparent	milky white which settles on standing	light amber, transparent	opaque black acid fumes, odor, some sediment	amber, transparent
Rex 49 Annealed	Weight change, mg/cm^2	-3.95	-.29	0.0	-5.42	-6.67
	Appearance of specimen	severe pitting	green and red tint	dull	dark brown coating	dark brown coating
	Appearance of fluid	colorless, transparent	milky white which settles on standing	light amber, transparent	opaque black, acid fumes, odor, some sediment	amber, transparent
Fresh fluid	Appearance of fluid	colorless, transparent	clear with light yellow	pale yellow, transparent	clear with faint haze	colorless, transparent

TABLE 16. MATERIALS WHICH SHOWED APPRECIABLE WEIGHT LOSS IN COMPATIBILITY TESTS CONVERTED TO THICKNESS LOSS

IN COMPATIBILITY TESTS

Thickness Loss, Mils

	PR-143AB		MLO 60-294		MCS-293		MCS-3101		F-50	
	72 hrs	3000 hrs	72 hrs	3000 hrs	72 hrs	3000 hrs	72 hrs	3000 hrs	72 hrs	3000 hrs
K-82							.07	2.91		
Ti-8 Mn							.28	11.64		
AISI-321							.28	11.64		
17-7 PH							.09	3.72		
Ti 7 Al 4 Mo							.87	36.0		
Ti 6 Al 4V							.71	29.55		
1009 Steel							.17	7.05	.19	7.89
Nitralloy G 135 modified							.24	9.99	.10	4.14
NM-100	.20	8.31					.37	15.39	.28	11.64
Rex 49	.20	8.31					.27	11.22	.34	14.13
Dynalloy 600							4.56	18.99		
Silver							+.06	+2.49		
Copper					.14	5.82	3.38	140.7		
Cadmium	.12	5.00					disintegrated		.15	6.24
440 C annealed	.35	14.58					.27	11.22		
440 C hardened							.17	7.05		
D-2 Ductile iron					.08	3.33	.27	11.22	.07	2.91
M-10 hardened	.08	3.33					.62	25.80	.10	4.14
M-50 hardened	+.08	+3.33					.22	9.15	.17	7.05
Hastelloy D							.15	6.24		
M-2 annealed	.28	11.64								
Aluminum							disintegrated			

Values at 3000 hours are extrapolated from 72-hour test data.

TABLE 17. ANALYSES OF MCS-3101 FLUIDS FROM MATERIAL COMPATIBILITY TESTS

(72 Hours at 600°F in a nitrogen Atmosphere)

Specimen	Specimen[2] Weight Loss mg/cm^2		Neut. No.[2]
Haynes 25	- .86	Solids, trace phenol, trace HX[3]	-
AISI-321	-1.57	Solids, phenol, no HX	-
Ti-6Al-4V	-7.99	Trace solids, very strong HX	5.5
Inconel X	- .40	Solids, phenol, strong HX	2.1
René 41	- .82	Heavy solids, phenol, strong HX	2.5
Ti-7Al-4Mo	-9.91	Solids, slight phenol, slight HX	7.1
17-4PH	-1.83	Solids, phenols, strong HX	3.4
K 96, WC-Co	- .06	Solids, phenols, HX	-
K 82, WTiC	-1.96	Solids, phenols, trace HX	-

Note: (1) Monsanto data

(2) Republic Aviation data

(3) Halide compound of HCl and/or HBr

TABLE 18. CORROSION TEST, DUPONT FLUID, PR-143AB

Change in weight, mg/cm^2	PR-143 AB 550°F-72 hrs. inert atmosphere	PR-143 AB Lot 4 550°F-72 hrs 5 L. air/hr.	PR-143 650°F-72 hrs. 5L. air/hr. washer (annealed)	PR-143 650°F-72 hrs. 5L. air/hr. balls (max. hardness)	PR-143 AB 600°F-72 hrs. Inert Atmos.
Aluminum		-0.66			
Aluminum bronze		-0.84			
Silver		-3.54			
52100 Steel	-0.36				-1.01
M-1 Tool steel	-0.43		-11.49	-1.53	-0.45[1], -0.63[2]
M-50 Tool steel	-0.75		-21.15	-1.95	-0.81
Steel, QQ-S-636		-0.75			+0.03
WADC-65				03.45	
AISI-301		-0.48			+0.30[3]
AISI-440C	-0.63	-1.23	-13.59	-8.19	-0.51[1], -0.39[2]
Monel 400	-0.48				-1.41
Titanium					+0.39 -0.05
Titanium (8Mn)		-0.96			
Titanium (7AL-4Mo)	-0.81				
Rex 49	-0.39		-10.65	-1.44	-0.42

NOTES:
(1) annealed condition
(2) heat treated
(3) 20 L. air/hr

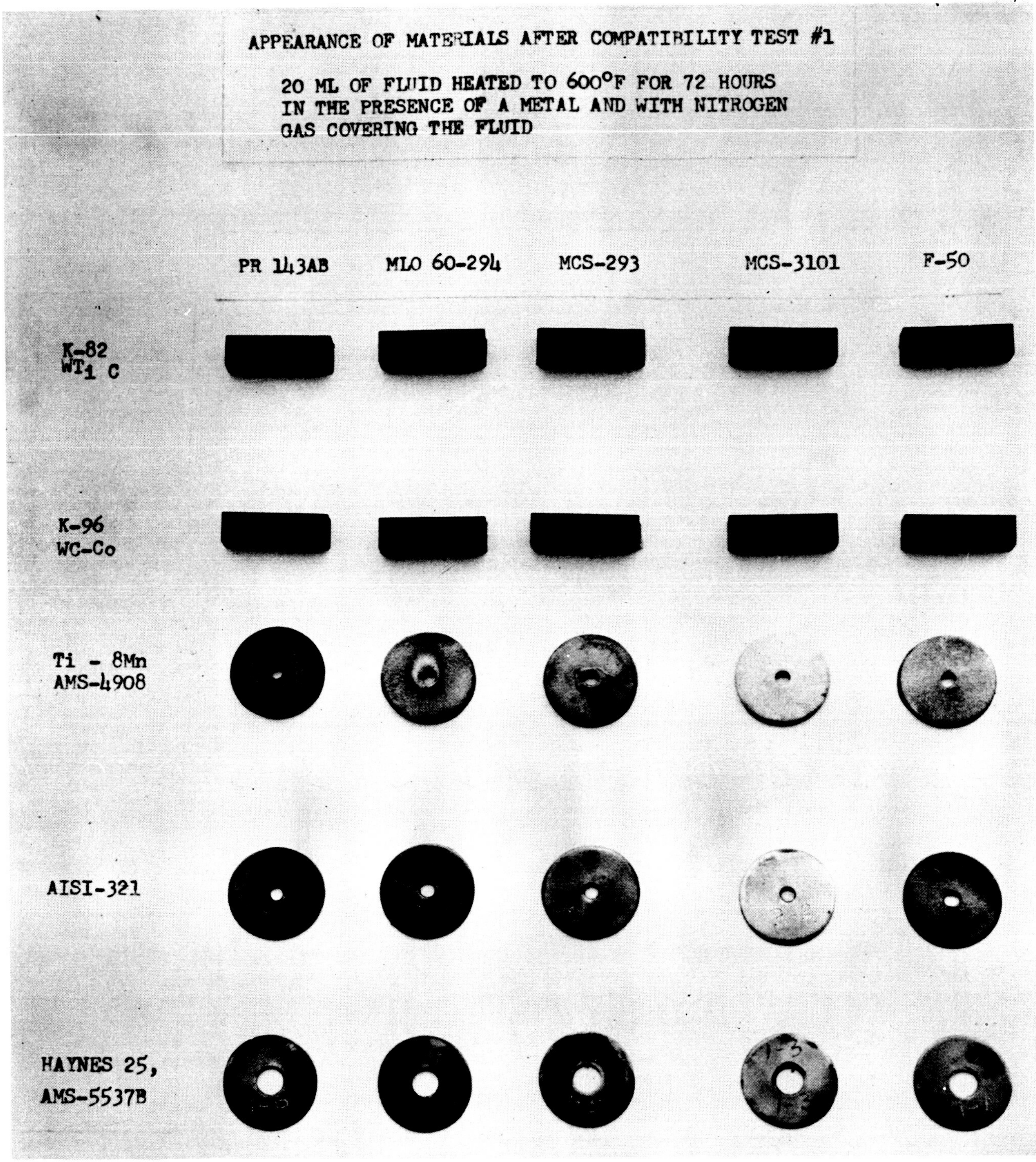

Figure 15. Appearance of Materials After Compatibility Test #1

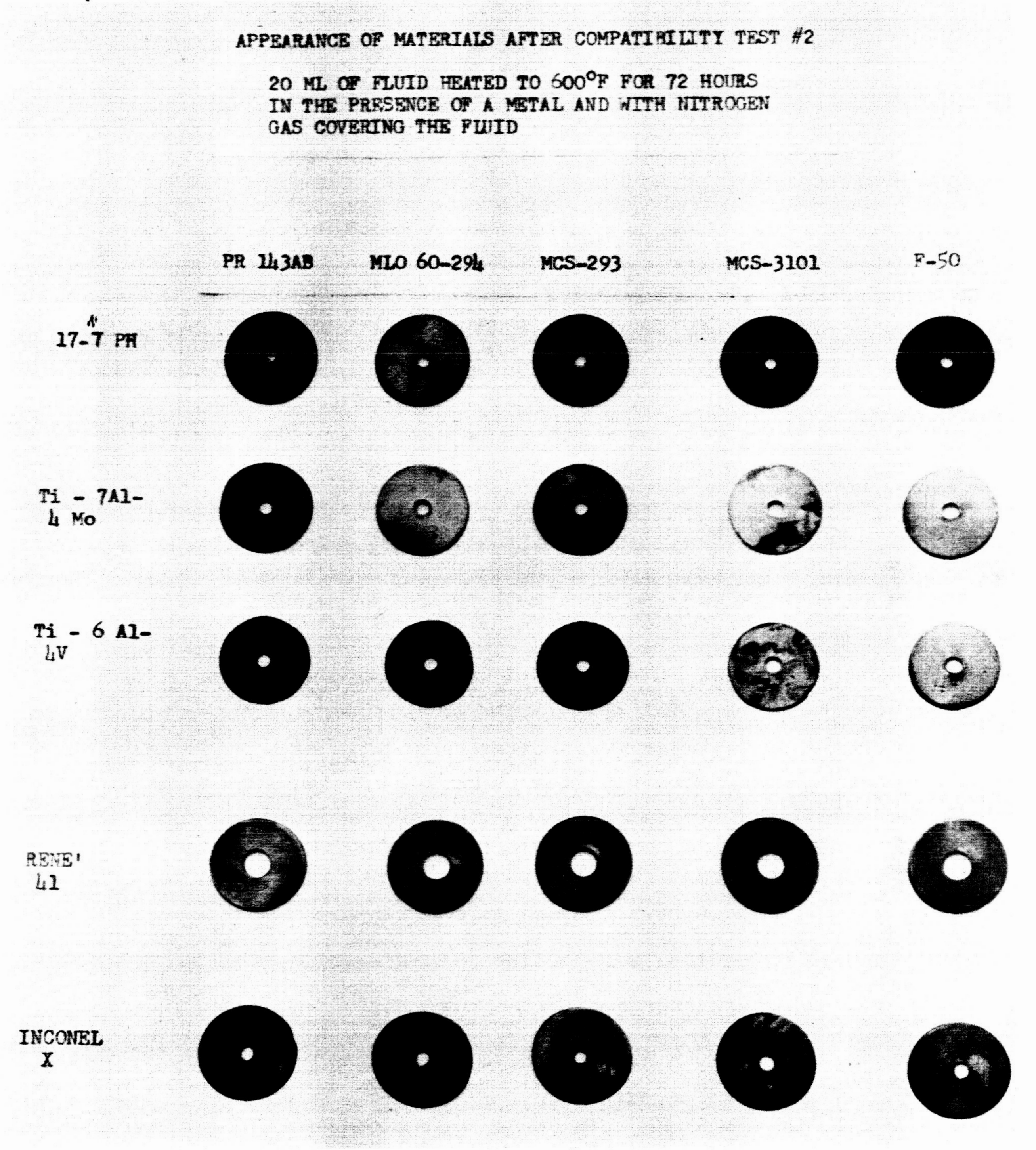

Figure 16. Appearance of Materials After Compatibility Test #2

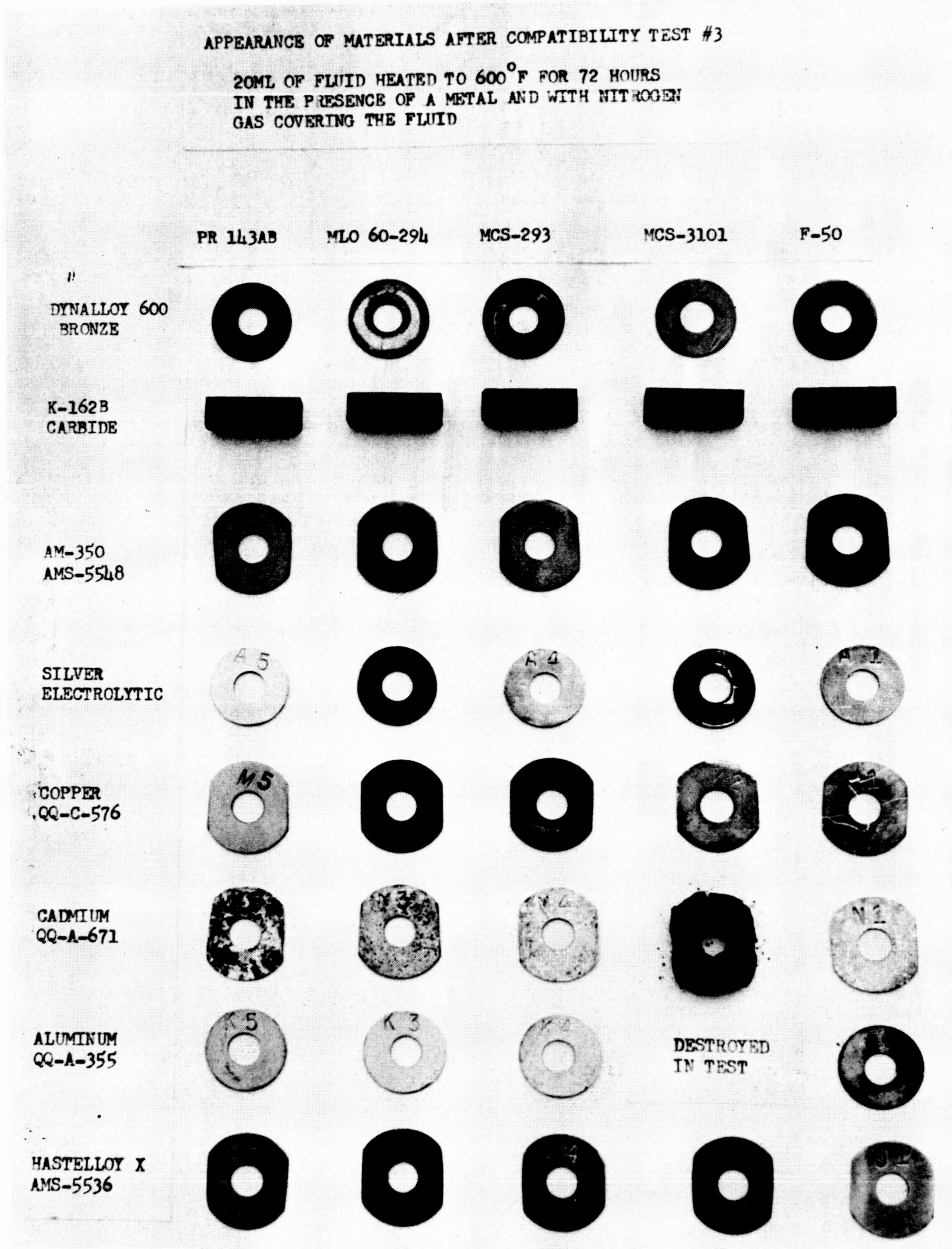

Figure 17. Appearance of Materials After Compatibility Test #3

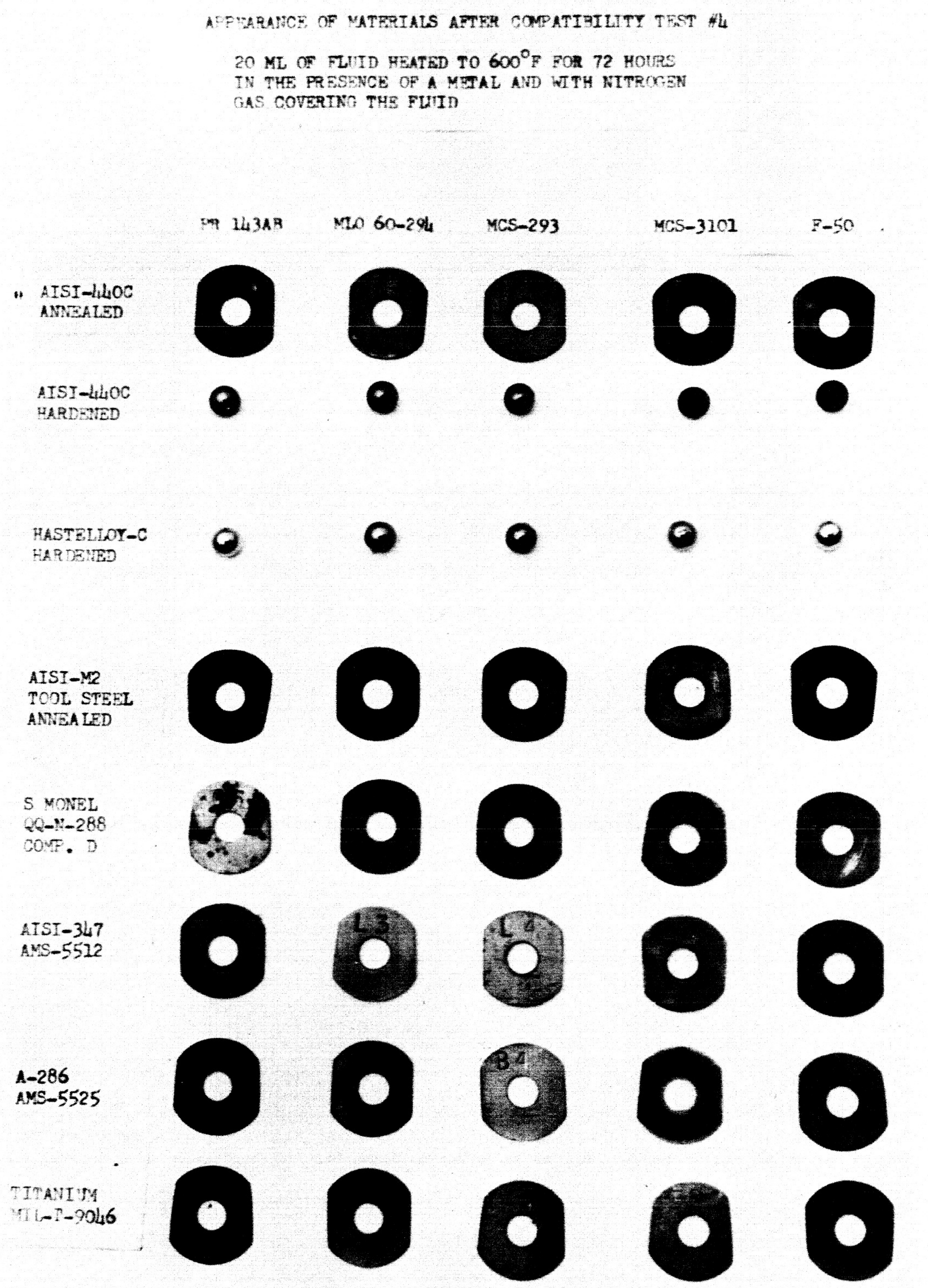

Figure 18. Appearance of Materials After Compatibility Test #4

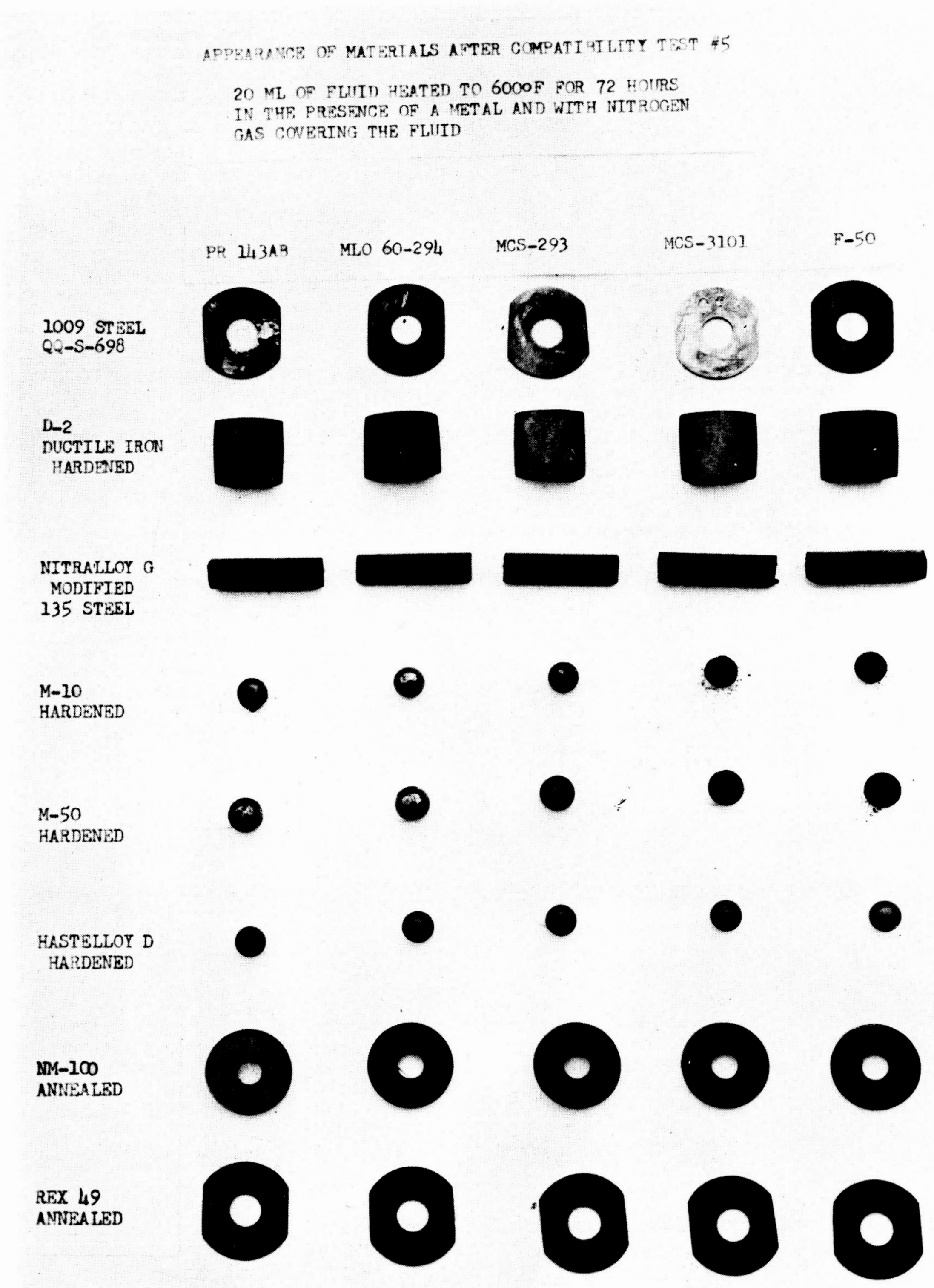

Figure 19. Appearance of Materials After Compatibility Test #5

The net result of these tests and the thermal stability tests described earlier indicate that the MCS-3101 fluid is marginal at 600°F. The exact process of deterioration is not well defined, but appears to be some combination of thermal instability and incompatibility with most of the proposed construction materials. The fluid vendor indicated, after a discussion of the test results, that at the time MCS-310 was formulated, their objective was a fire-resistant fluid with long term thermal stability at 400-450°F with short excursions at higher temperatures.

Compatibility test data, supplied by the fluid manufacturers under varying test conditions comprise Tables 18 to 25.

h. Specific Heat and Thermal Conductivity

Data on specific heat and thermal conductivity were supplied by the fluid manufacturers (see Tables 26 and 27 and Figures 20 and 21). For ease in comparison, the values were converted to the same units.

It is important to note that anticipated aircraft compartment temperatures may rise as high as 600°F, so that heat dissipation from the hydraulic system to the ambient will be low. Also, future hydraulic systems will be extremely large as compared to current systems. Therefore, those fluids with high thermal stability and with good heat transfer properties will minimize the weight penalties of heat exchanger size in transferring the heat to heat sinks.

i. Pour Point and Nitrogen Solubility

Pour point and nitrogen solubility data, as shown in Tables 28 and 29, were supplied by the fluid vendors.

j. Toxicity

As a standard practice, it is recommended that precautionary measures employing protective eye equipment, rubber gloves, careful washing of exposed skin, and adequate ventilation be taken when handling any of the experimental fluids. Preliminary screening of the fresh fluids found them of be nontoxic during normal use. However, MCS-310 is a mild eye and skin irritant (Reference 11).

TABLE 19. CORROSION TEST, MONSANTO FLUID MCS-293

Change in weight, mg/cm^2	MCS-293 100 ml fluid, 600°F-48 hrs. 5L. air/hr.	MCS-293 100 ml fluid 500°F-48 hrs. 5L. air/hr.	MCS-293 100 ml fluid, 500°F - 48 hrs; 5L. air/hr.					
			Nickel Silver	Aluminum Bronze #3	Silicon-Iron Bronze	Alcop	Phosphor Bronze	Gear Bronze
Aluminum	-0.22	0.00	+0.04	0.00	+0.01	+0.02	+0.01	+0.07
Copper	-8.37	3.97						
Copper alloy			0.00	+0.66	-1.91	+0.31	-0.15	-0.59
Magnesium	+0.48	+0.03	+0.21	-0.09	+0.32	+0.25	+0.24	+0.19
Silver	-1.39	-0.71	-0.25	-0.25	-0.17	-0.11	-0.13	-0.24
Iron	+0.23	+0.04	+0.13	+0.13	+0.14	+0.15	+0.15	+0.10
Titanium	+0.16		+0.04	+0.06	+0.06	+0.05	+0.10	+0.08
Viscosity, Initial	+42.3% change @ 100°F							+6.5% change @ 100°F
Final	+20.8% change @ 210°F							+4.4% change @ 210°F
Acidity, Initial, mg KOH/g	0.01							0.01
Final	0.15							0.10

TABLE 20. CORROSION TEST, MONSANTO FLUID MCS-310

Change in weight, mg/cm^2	MCS-310 100 ml fluid, 250°F, -168 hrs. 5L air/hr.	MCS-310 100 ml fluid, 550°F-24 hrs. 5L air/hr. DRY AIR	MCS-310 100 ml fluid, 550°F-24 hrs. 5L air/hrs. SATURATED AIR	MCS-310 100 ml fluid 550°F-24 hrs. nitrogen blanket	MCS-310 100 ml fluid 550°F-24 hrs. nitrogen blanket
Aluminum	0.00				
Aluminum Alloy 6061					+0.19
Copper	0.00				
Aluminum Bronze		+0.18	+.90	-0.19	-0.07
Magnesium	0.00				
Silver		+4.44	+3.99	+0.12	+0.14
Iron	0.00	+0.29	+0.48	+0.71	+0.22
Cadmium/Steel	+0.02				
Titanium		0.00	+.06	0.00	+0.02
Viscosity, Initial, cs	2.83 @ 130°F	2.83 @ 130°F	2.83 @ 130°F	2.80 @ 120°F	2.79 @ 130°F
Final	2.85 @ 130°F	2.94 @ 130°F	2.92 @ 120°F	2.84 @ 130°F	2.88 @ 130°F
Acidity, Initial, mg KOH/g	0.013	0.12	0.12	0.00	0.06
Final	0.016	0.07	0.06	0.00	0.06
Fluid Appearance	faint yellow, clear transparent	dark opaque	dark opaque	yellow-brown transparent	dark yellow-brown, semi-transparent

TABLE 21. CORROSION TEST, HUMBLE OIL FN 3160 AND GENERAL ELECTRIC F-50 FLUIDS

Change in weight, mg/cm^2	MLO 60-294 100 ml fluid, 347°F-48 hrs. 5L. air/hr. (FN 3160)	F-50 400°F-72 hrs. 5L. air/hr.	F-50 450°F-72 hrs. 5L. air/hr	F-50 500°F-48 hrs. 5L. gas/hr. 95% N2, 5% O_2
Aluminum		0.02	0.02	
Copper	-0.06	0.04	0.03	
Magnesium			0.03	
Silver	0.00		0.05	
52100 Steel				0.05
AM-350	0.00			
AM-355	0.00			
AISI-440C	0.00			0.02
Titanium		0.03		0.06
Viscosity, Initial, cs	15.08 @ 100°F			
Final	17.12 @ 100°F	0% change @ 100°F	+20% change @ 100°F	+5% change @ 100°F
Acidity, Initial, mg KOH/g	0.02			
Final	1.67	0.02 increase	0.10 increase	0.15 increase
Fluid appearance	moderate amber, no precipitate			

TABLE 22. MCS-310 VERSUS ELASTOMER COMPATIBILITY

Federal Test Method Standard No. 791 - 3603.2
168 Hours Immersion @ 160°F

	Shore A Hardness		Volume Change
	Initial	Final	
EPR 56551-44	77	65	+38.5%
Butyl SR-613-75	82	67	+49.8
Nitrile 7474-70	75	62	+128.0
Viton 920-70	77	71	+1.93
168 Hours Immersion @ 450°F			
Viton B SR-278-70	76	74	+8.90
Fluorosilicone 1000-70	66	10	Severe degradation

TABLE 23. ELASTOMER COMPATIBILITY WITH PR-143, LOT 2

	Material	psi Tensile	% Elongation	Shore Hardness	% Loss Tensile	After Immersion 168 Hours at 500°F		% Volume Change
						% Loss Elongation	Change Hardness	
T-23	Triazine	220	120	58	+20	-25	+10	5.7
F-3	Viton A HV	1675	110	84	Brittle	--	--	17.5
F-72	Viton B	1965	275	76	Brittle	--	--	18.0
F-34	Viton A	1995	180	81	Brittle	--	--	21.0

Fluid Condition After Tests (Visually Inspected):

200°F - Cloudy
300°F - Cloudy - pieces of rubber floating or dispersed in liquid.
400°F - Cloudy - pieces of rubber floating or dispersed in liquid.
500°F - Black - no viscosity change - had large expansion at 500°F.

TABLE 24. ELASTOMER AND PLASTIC COMPATIBILITY WITH PR-143, LOT 2

	Material	Original Physicals				After Immersion 168 Hours at 200°F		
		Tensile psi	Elongation %	Hardness Shore	% Loss Tensile	Elongation	Hardness	% Volume Change
LS63	Fluorosilicone	1590	310	44	28	17	+13	+0.8
4021	Ethyl Acrylate	1850	280	70	0	16	+5	+0.7
K1046	Methyl Silicone	990	280	55	17	11	+11	1.3
AMS-D	Viton A	2800	175	85	16	0	+2	+0.8
61-19-C	Urethane	2900	290	90	+2	-28	+2	+0.9
8C	Hypolon	4740	160	91	+1	31	0	0.9
18D	Butyl 325	2460	400	67	15	25	+6	1
2543	VFA	2300	390	80	23	14	0	-3
2544	Natural Rubber	985	150	78	68	43	-1	0.2
8B	Neoprene WRT	2330	160	82	2	40	+9	0.3
H Stock	Hycar 1001 (Buna-N)	3820	500	67	10	40	+12	0
26B	Polysulfide-Thiokol SF	975	260	66	25	+25	+1	0.8
14B	Cis 1, 4-Polybutadiene	1720	340	68	58	68	+13	0.7
21E	Sympol 1013, SBR	3230	500	70	49	52	+6	+1.3
A87	EPT - Sulfur Cure	4360	500	76	33	40	+3	1.4
A184	EPT - Peroxide Cure	4590	740	63	+2	5	+5	1.3
341A	XP-139, Polypropylene Oxide	2480	790	55	--	--	--	--
340A	Cyanacryl, Acrylic Rubber	1460	355	57	--	--	--	--
E21	Vibrathane (Urethane)	3330	160	86	--	--	--	--

TABLE 25. MCS-310 COMPATIBILITY WITH OTHER FLUIDS

Material	Initial Appearance	Final Appearance	Change in Viscosity @ -40°F
Trichloroethylene	Clear, colorless solution	Clear, yellow solution	None
Tetrachloroethylene	Clear, colorless solution	Clear, pale yellow solution	None
Petroleum Ether	Clear, colorless solution	Clear, pale yellow solution	None
2% Isopropyl Alcohol 1% Ethylene Glycol 1% Propylene Glycol	Clear, colorless suspension	Clear, colorless suspension	None
Skydrol 500A	Clear, colorless solution	Clear, pale yellow solution	None
Mobil Jet Oil II	Clear, golden solution	Clear, amber solution	None
MCS 293	Clear, colorless solution	Clear, yellow solution	None
MIL-H-5606A	Clear, pink solution	Clear, amber solution	None

These tests were run to determine effect of contaminants on MCS 3100. Solutions 4% by weight of contaminant wsre made and were heated at 150°C (302°F) for 48 hours.

TABLE 26. SPECIFIC HEAT (Btu/lb/°F) OF FLUIDS[1]

F-50[2]	MLO-60-294[3]	PR-143AC[4]	MCS-293[5]	MCS-310[6]
.33 @ 0°F	.462 @ 100°F	.226 @ 100°F	.312 @ 0°F	.23 @ -40°F
.51 @ 500°F	.489 @ 150°F	.249 @ 200°F	.347 @ 100°F	.25 @ 32°F
	.516 @ 200°F	.272 @ 300°F	.383 @ 200°F	.27 @ 122°F
	.544 @ 250°F	.295 @ 400°F	.418 @ 300°F	.29 @ 212°F
	.571 @ 300°F	.317 @ 500°F	.452 @ 400°F	.31 @ 302°F
			.488 @ 500°F	.34 @ 392°F

NOTES:

(1) Fluid manufacturers' data

(2) General Electric Technical Data Book S-10A, Versilube Silicone Lubricants

(3) Determined by Petroleum Refining Laboratory, Pennsylvania State University, July 27, 1964

(4) PR-143AC is the engine oil grade of the fluorocarbon fluid. Determined by Phoenix Chemical Laboratory, Inc., Chicago, Illinois using the Drop Method of mixtures procedure.

(5) Estimated data by Monsanto

(6) Determined by direct calorimetry below 100°C and by the method of mixtures above 100°C

TABLE 27. THERMAL CONDUCTIVITY (Btu/hr/ft^2/°F/ft) OF FLUIDS[1]

F-50	NUTO H44[2] similar to (MLO-60-294)	PR-143AC[3]	MCS-293[5]	MCS-310[4]
.089 @ 50°F	.072 @ 32°F	.0537 @ 100°F	.068 @ 0°F	.064 @ -40°F
.087 @ 77°F	.070 @ 77°F	.0508 @ 300°F	.071 @ 100°F	.064 @ 32°F
.077 @ 300°F	.073 @ 122°F	.0508 @ 500°F	.072 @ 200°F	.063 @ 122°F
	.067 @ 167°F		.069 @ 300°F	.061 @ 212°F
			.065 @ 400°F	.060 @ 302°F
			.059 @ 500°F	.058 @ 392°F

NOTES:

(1) Fluid manufacturers' data

(2) Determined by National Engineering Laboratory at East Kilbride, Glasgow. NEL Report No. 81, April 1963. Data obtained by steady-state hot-wire method. Accuracy estimated to be within ± 5%. Calculated best straight line through four points is:

$k = (.07245 - .0000479\ T)$ Btu/hr/ft^2/°F/ft within temperature range of 32°F to 167°F.

(3) Determined by Phoenix Chemical Laboratory, Inc., Chicago, Illinois using Hot Wire Method. PR-143 AC is the engine oil version of the fluorocarbon fluid.

(4) Determined by modified hot wire technique as reported in Chemical and Engineering Data Series, Vol. 2, No. 1, August 1957, Page 54, "Thermal Conductivity of Some Organic Liquid High Temperature Measurements", by O.B. Cecil, W.E. Doerner, and R.H. Munch.

(5) Estimated.

TABLE 28. POUR POINTS OF SEVERAL FLUIDS

Fluid	Temperature, °F
PR-143 AB	-50
MLO 60-294	-70
MCS-310	-60
MCS-293	-20
F-50	<-100
XF-1-0291	< -80
XF-1-0294	< -70
XRM-154D	< -65

TABLE 29. NITROGEN SOLUBILITY

MLO 60-294 (Source: ML TDR 64-68, Fluids, Lubricants, Fuels and Related Materials, Petroleum Refining Laboratory)

Temperature, °F	75	167	210	310	390
Oxygen, ppm wt.	.2	.2	.2	.6	.5
Nitrogen, ppm wt.	112	120	131	152	189
Total, ppm wt.	112	120	120	153	190

PR-143 AC (Source: DuPont)

1. Nitrogen Solubility

Temperature, °F	210	250	300	350	400
Nitrogen, ppm wt.	114	115	116	118	119.5

2. Air Solubility (Source: DuPont)

Temperature, °F	190	260	310	390
Oxygen, ppm wt.	35.5	36.5	47	38
Nitrogen, ppm wt.	83	88.5	92.5	99

MCS-310 (Source: Monsanto)

	MCS-310		MIL-H-5606	
Fluid @ 73°F and 1 atm				
Gas @ 73°F and 1 atm	N_2	Air	N_2	Air
Bunson gas coefficient @ STP (initial $\frac{\text{vol. gas}}{\text{vol. fluid}}$ = 1.35)	.10	.11	.11	.14
Gas evolution characteristic	evolution slow and difficult	evolution slow	foams	foams

XF-1-0291 (Source: Dow Corning)

Absorption coefficient (N_2 @ 25°C) = $1.568 \times 10^{-4} \frac{\text{cc } N_2}{\text{g oil mm Hg}}$

F-50 (Source: General Electric)

Approximate solubility of air in F-50 fluid

Temperature, °F	77	100	200	300	350
Air, % by volume	22	16	7.8	5.7	5.2

XF-1-0294 (Source: Dow Corning)

N_2 Solubility coefficient @ 77°F = $1.573 \times 10^{-4} \frac{\text{cc gas}}{\text{g oil-mm Hg}}$

O_2 Solubility coefficient @ 77°F = $2.250 \times 10^{-4} \frac{\text{cc gas}}{\text{g oil-mm Hg}}$

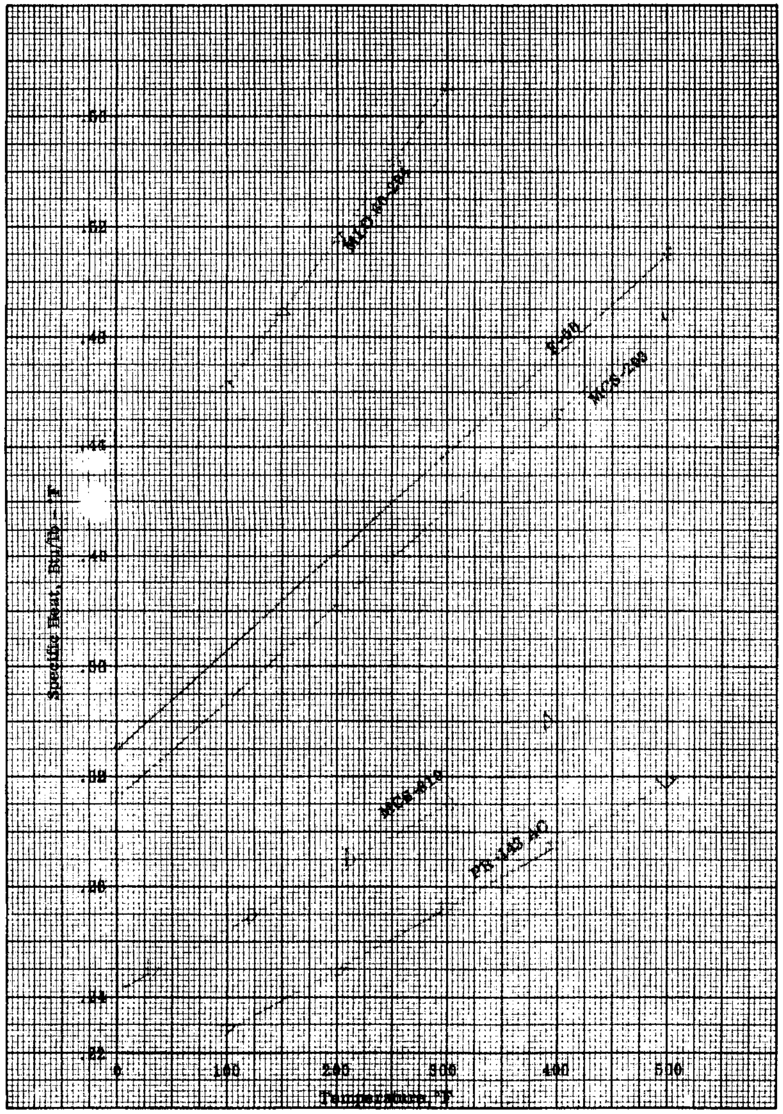

Figure 20. Specific Heat of Fluids

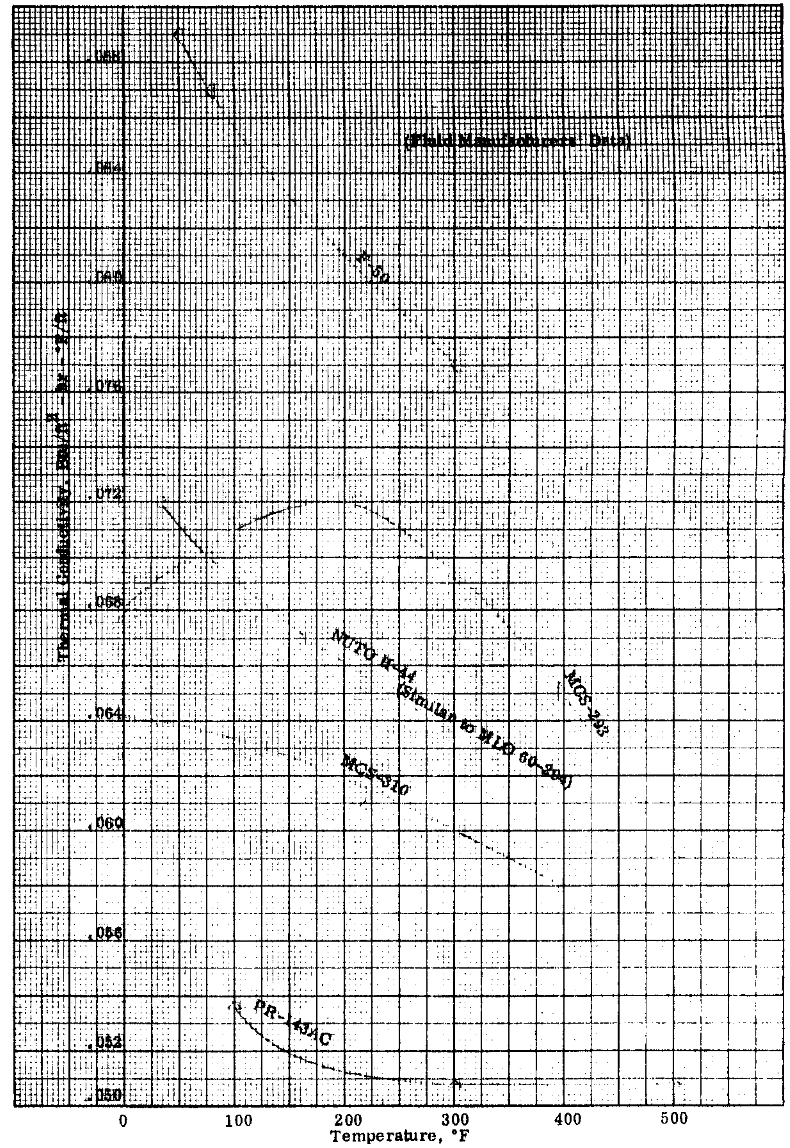

Figure 21. Thermal Conductivity of Fluids

Until more definitive information is available, it is recommended that whenever fluids PR-143AB (Reference 12), MCS-293 (Reference 13), F-50 (Reference 14), MCS-310 (Reference 11), and MLO 60-294 (Reference 15) are handled above 450°F, efficient and continuous ventilation be employed to avoid any exposure of personnel to potential decomposition products.

C. RATINGS OF FLUIDS

Candidate fluids were rated (see Table 30) on the basis of their known properties as discussed in the preceding subsection. Lubricating ability was not included in the ratings. This very important property will be the major factor investigated during the pump tests.

PR-143AB fluorocarbon has excellent thermal stability and fire resistance, which are two of the most important properties of a hydraulic fluid. On the other hand, PR-143AB has a high density, a poor bulk modulus, poor heat transfer properties, and is presently very expensive. Therefore, the ultimate suitability of this fluid remains to be determined.

The fluid which appears to possess well-rounded properties, with the exception of low temperature viscosity, is MCS-293 modified polyphenyl ether. However, this single deficiency may present less of a problem for the system designer than PR-143AB.

MLO 60-294 mineral oil possesses slightly better properties than F-50 silicone, with the exception of fire resistance. The poor fire resistance of the mineral oils imposes a major hazard. The poor thermal stability of F-50 has downgraded its potential.

MCS-3101 polyaryl fluid, according to the manufacturer, was formulated for use in the temperature range of 400°F to 500°F. It therefore did not rate well in evaluations conducted at 600°F.

On the basis of a comparison of thermal stability and some fire resistance properties, XF-1-0291 silicone appears better than or equal to F-50 silicone.

TABLE 30. SUMMARY OF FLUID RATINGS

	MCS-293		F-50		PR-143AB		MLO 60-294		MCS-3101		XF-1-0291	XF-1-0294	XRM-154D
Thermal Stability	G	2	P	4	E	1	F	3	P	5	G	G	F
Hot Manifold	G	3	F	4	E	1	P	5	E	2	-	-	-
Ignition Spray	G	2	F	3	E	1	P	5	P	4	-	-	-
AIT	G	3	G	4	E	1	P	5	E	2	G	G	F
Fire Point	F	3	G	2	E	1	P	5	F	4	E	G	G
Flash Point	F	3	F	2	E	1	P	4	P	5	G	F	G
Bulk Modulus	G	1	P	4	P	5	F	3	G	2	P	P	-
Vapor Pressure	G	2	E	1	F	3	F	4	P	5	G	G	-
Materials Compatibility	G	2	F	4	F	3	G	1	P	5	-	-	-
Specific Heat	F	3	F	2	P	5	G	1	P	4	-	-	-
Thermal Conductivity	F	2	G	1	P	5	F	3	P	4	-	-	-
Density	F	3	G	2	P	5	E	1	P	4	G	F	F
Viscosity	P	2	E	1	P	4	P	3	P	5	E	P	E

E = Excellent, G = Good, F = Fair, P = Poor

1 = Best, 5 = Worst

TASK II - DETERMINATION OF LUBRICATING CHARACTERISTICS

A. SELECTION OF BEARING MATERIALS

The purpose of this task is to arrive at suitable pump bearing materials for use with each of the five candidate fluids in the pump loop tests of Task III. Four bearing material combinations for each fluid were selected and are to be screened in a rider-on-disk boundary lubrication tester.

The choice of bearing materials for evaluation in the lubrication tester is based on their ultimate use in a high temperature pump under the following conditions: (1) a maximum pump fluid inlet temperature of 600°F, (2) 3000-hour life, (3) sliding speeds to 3000 fpm, (4) bearing pressures of 1500 to 2000 psi, (5) fluids in the degassed state, (6) compatible system materials, and (7) bearing materials operable under boundary lubrication.

High temperature bearing materials are available in several categories, including the bronzes, copper-nickel alloys, tool steels, stainless steels, super alloys, and cermets. Composition of the bearing materials selected are shown in Table 31.

Bronzes are presently used at temperatures to about 500°F. At these temperatures the bronze tends to lose its hot hardness (Figure 22) and dimensional stability. However, below this temperature the bronzes have good wear and frictional properties when run on tool steel intended for application with silicone or mineral oils (Reference 16). Pheldor 10, an iron-silicon-bronze, has been selected as a candidate bearing material for F-50 and MLO 60-294 fluids. In addition to exhibiting low friction and wear it also possesses high strength among the bronzes.

Tool steels such as the molybdenum-based M-2, M-10, and M-50 have good hardness retention, dimensional stability and wear resistance at elevated temperatures. M-2 tool steel was selected for testing with F-50 and MLO 60-294 fluids because of satisfactory past performance (Reference 16).

TABLE 31. COMPOSITION OF BEARING MATERIALS

	Bronze	Ni-Cu Alloy	Tool Steel	Stainless Steel		Super Alloy			Cermet		
	Pheldor 10	S-Monel	M-2	440C Mod.	NM-100	Star J	Hastelloy D	Co-Mo	K-82	K-96	K-162B
Carbon		.08	.8	1.1	1.25	2.5	.12		6.7	5.8	13.2
Iron	.8	2	Bal.	Bal.	Bal.	3	2				
Cobalt					9.5	Bal.	1.5	75	13.0	5.8	
Silicon	3	4	.3	1		1	9				
Tungsten			6		10.5	17			66.4	86.4	
Manganese	1.5	.8	.25	1		1	1				
Nickel	.6	63				2.5	Bal.				25.0
Chromium			4	14	17.5	32	1				
Copper	97	29.5					3				
Titanium									6.3		52
Vanadium			2		.75						
Molybdenum			5	4				25			5.0
Zinc	1.5										
Lead	.05										
Sulfur		.008									
Columbium									4.1		4.5
Tantalum									3.5	2.0	.3
Others						2					

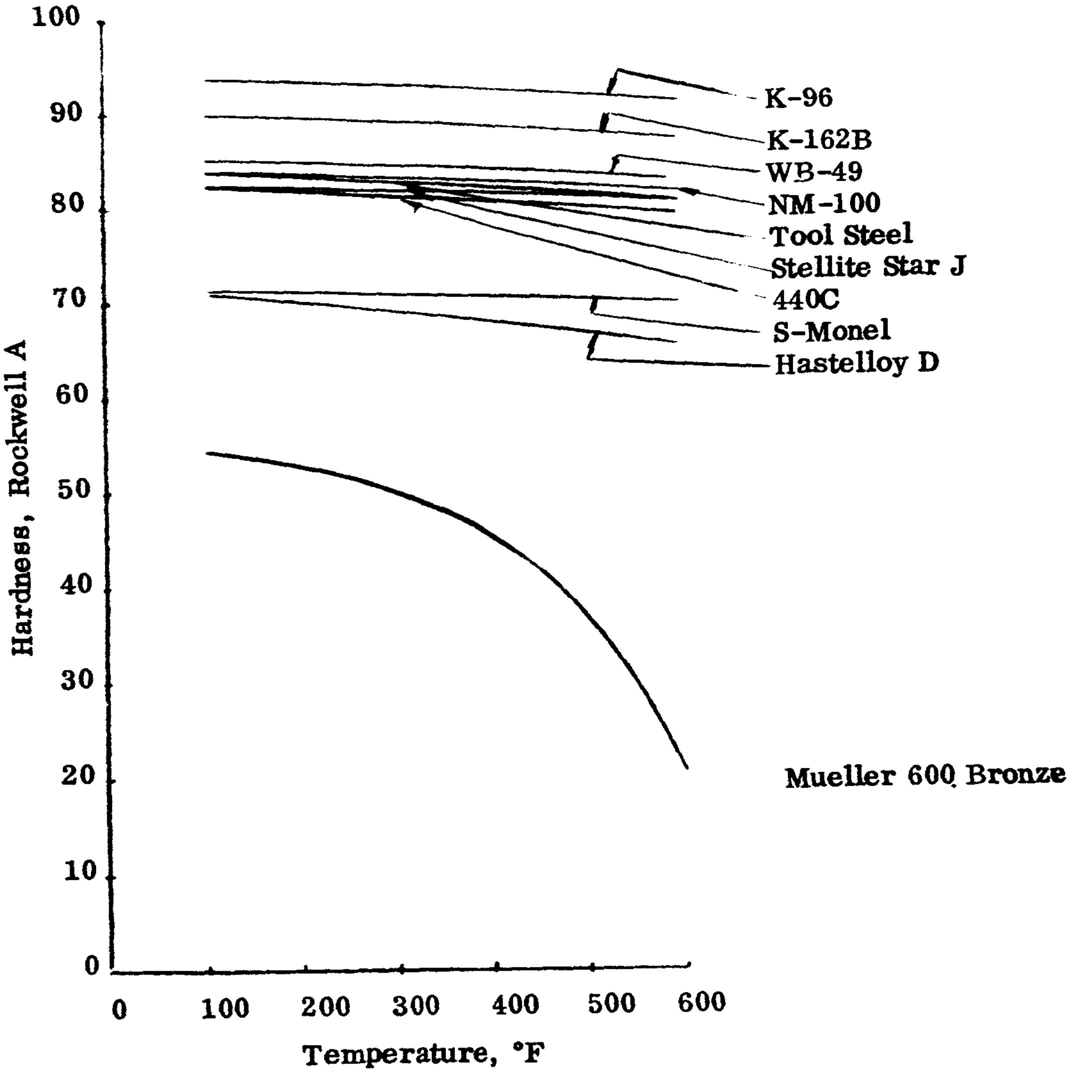

Figure 22. Hot Hardness Temperature of Some Bearing Materials

Copper-nickel base alloys are superior to the bronzes in strength and corrosion resistance. Popular among this class are the Monels, which have been used as retained rings in high temperature bearings (Reference 17). S-Monel has been selected for evaluation with all fluids because of its resistance to galling and wear under corrosive conditions, and where little or no lubrication is provided.

Stainless steels are generally used as bearings where hot hardness and good corrosion resistance are required. AISI 440C modified (+ 4% Mo) and the more recent NM-100 (a product of Nuclear Metals Division) typify this class of materials. AISI 440C modified was selected for testing with MCS-3101 and PR-143 AB fluids. Because of insufficient property data, NM-100 is considered only as an alternate material for F-50 and PR-143AB, despite its promising use in rod end bearings. Alternate materials will be tested in the event that a primary candidate is ruled out for any reason.

Nickel-silicon alloys have shown excellent wear and friction properties which are attributed to hot hardness and the strong affinity of silicon for oxygen (References 17, 18, and 19). These alloys have also shown promising sliding characteristics in halogen-containing gases (Reference 25): Alloys of this type would probably be suitable for use with MCS-3101 and PR-143 AB fluids because the fluids contain halogens and the environment would be scarce in oxygen. Hastelloy D comes closest to possessing the 5 to 10% silicon necessary for the desired low friction and wear and was accordingly selected.

Super alloys with a nickel- or cobalt-base are generally preferred over the iron-base alloys because of better wear and oxidation resistance. Cobalt base alloys have lower friction than the iron- and nickel-base alloys at temperatures below 700°F (Reference 17). These materials have also shown excellent antigalling and antiseizing properties at elevated temperatures. Stellite Star J was selected as a candidate bearing material for all fluids because of its known superiority in resisting seizure.

Cermets are employed where hot hardness is required at very high temperatures. Refractory carbides have low thermal shock and impact strength. Maximum toughness and shock resistance are obtained by a high metal content, which acts as a binder, but at the expense of some wear resistance. K-82, K-96, and K-162B carbides were selected because of their low wear and antigalling properties.

In addition to the above materials for high temperature bearing applications, several self-lubricating materials exist. Techniques such as coating, diffusion bonding, and inclusion of additives were investigated by others using self-lubricating materials, such as molybdenum disulfide, calcium fluoride, sulfur, and the rare earths (References 20 to 22). Materials in this category were bypassed because of their lack of high strength.

The friction and wear behavior of certain metals has been related to their crystalline structure (References 23 and 24). Certain close-packed hexagonal metals with lattice ratio c/a of 1.633 have produced lower friction and wear than those in the body or face-centered cubic form. This difference is believed to be due mainly to the different patterns in slip behavior afforded by the crystal structure. One of the newer alloys, 25% molybdenum-cobalt alloy, has been selected as an alternate material for evaluation.

The bearing materials described above were discussed and coordinated with the NASA Program Manager and NASA technical personnel. The approved candidate bearing material combinations for evaluation in Task II are listed in Table 32.

B. DESCRIPTION OF THE BOUNDARY LUBRICATION TESTER

The boundary lubrication tester, of the rider-on-disk type, is designed to operate in a controlled inert-gas atmosphere. The tester is illustrated in Figures 23 to 26.

The rider-on-disk tester is designed to operate at loads of from one to over 10 pounds, at speeds up to 3000 feet per minute, at temperatures from 150° to 600°F, and in controlled inert-gas atmospheres. Three 1/4-inch diameter balls are held stationary in a cup, with a 2-inch diameter disk rubbing against the balls at an angular speed of up to 7600 rpm. The cup is supported at its center by a conical pin. Load is applied to the cup through a pneumatically actuated piston containing the conical pin. Initially, the cup was suspended on an air bearing, instead of the pin; however, the torque pickup was extremely sensitive to vibration transmitted from the motor through the tester. This background chatter was not picked up on the torque recorder with the pin support.

TABLE 32 CANDIDATE BEARING MATERIAL COMBINATIONS

	F-50	MLO 60-294	MCS-293	MCS-3101	PR-143AB
Ball	S-Monel	S-Monel	S-Monel	S-Monel	S-Monel
Disk	M-2	M-2	M-2	440 C mod.	440 C mod.
Ball	Pheldor 10	Pheldor 10	Stellite Star J	Hastelloy D	Stellite Star J
Disk	M-2	M-2	M-2	440 C mod.	440 C mod.
Ball	Stellite Star J	Stellite Star J	M-2	Stellite Star J	Hastelloy D
Disk	M-2	M-2	M-2 Mo coated	440 C mod.	440 c mod.
Ball	K82	K82	K82	K-82	K 162B
Disk	K96 or LW-1	K96 or LW-1	K96 or LW-1	K96 or LW-1	K96

Alternate Candidates

	F-50	MLO 60-294	MCS-293	MCS-3101	PR-143AB
Ball	NM-100	Hastelloy D	Co + 25% Mo	Co + 25% Mo	NM-100
Disk	NM-100	M-2	M-2	M-2	NM-100
Ball	Hastelloy D	M-2	M-2	NM-100	
Disk	M-2	M-2, Mo - coated	M-2	NM-100	

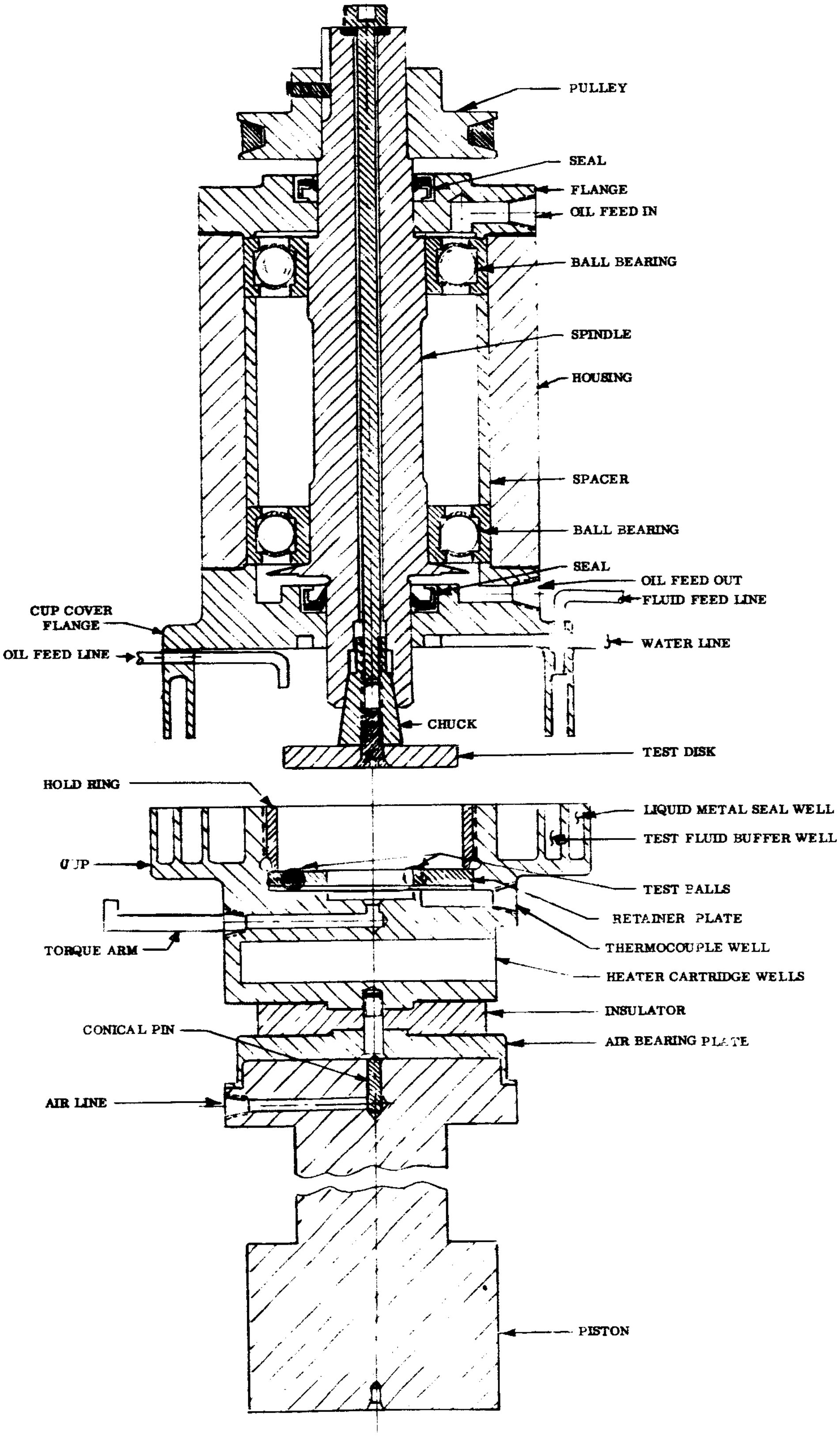

Figure 23. Schematic of Boundary Lubrication Tester Assembly

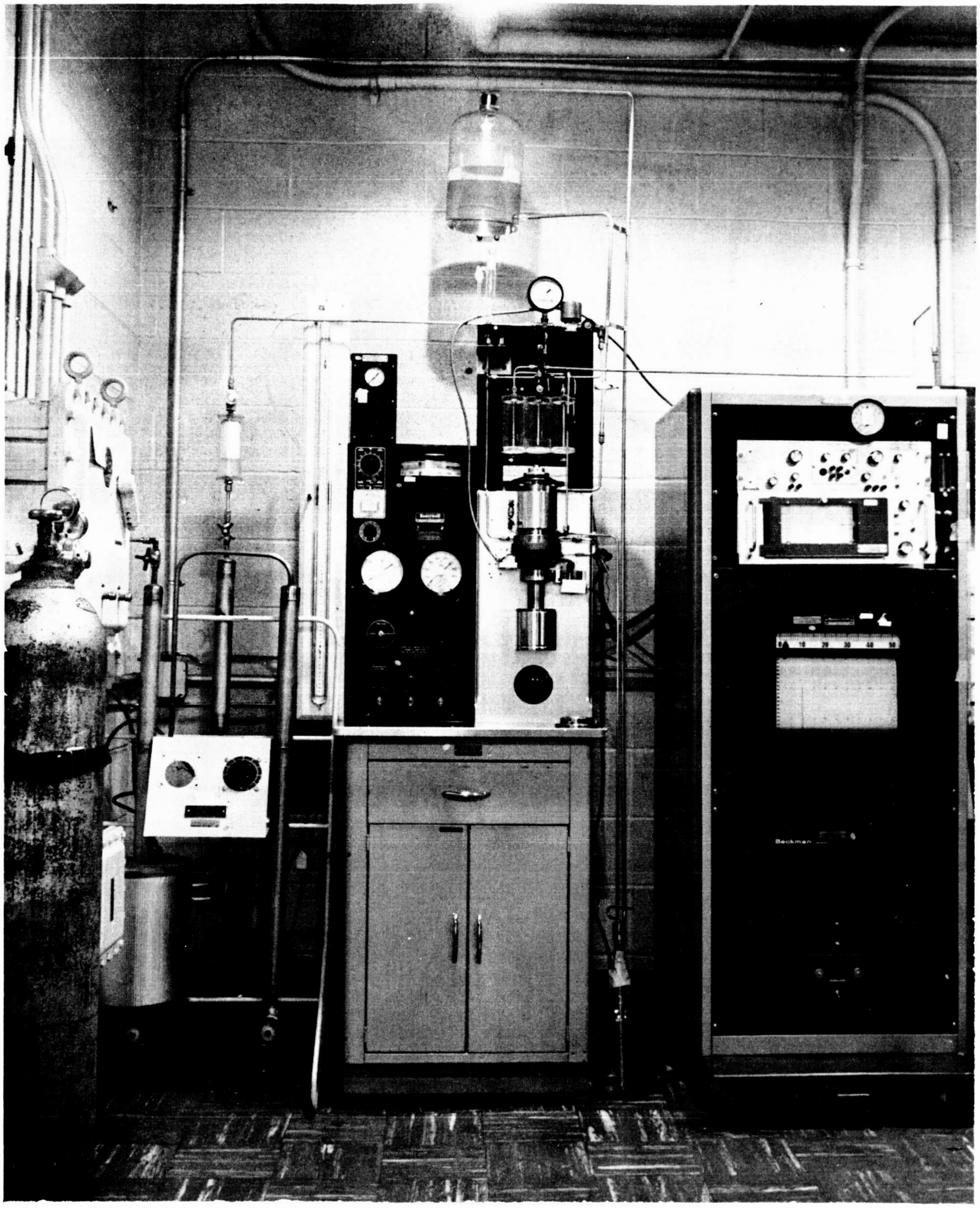

Figure 24. Inert Gas System, Lubrication Tester, Torque Recorder, and Oxygen Analyzer

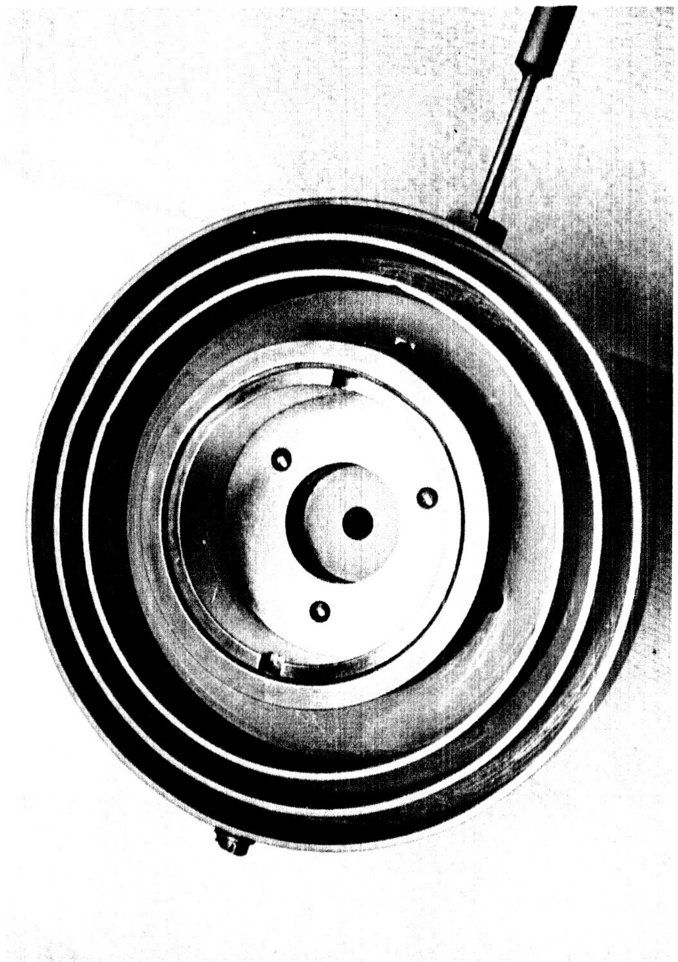

Figure 25. Test Cup Showing Three Test Balls

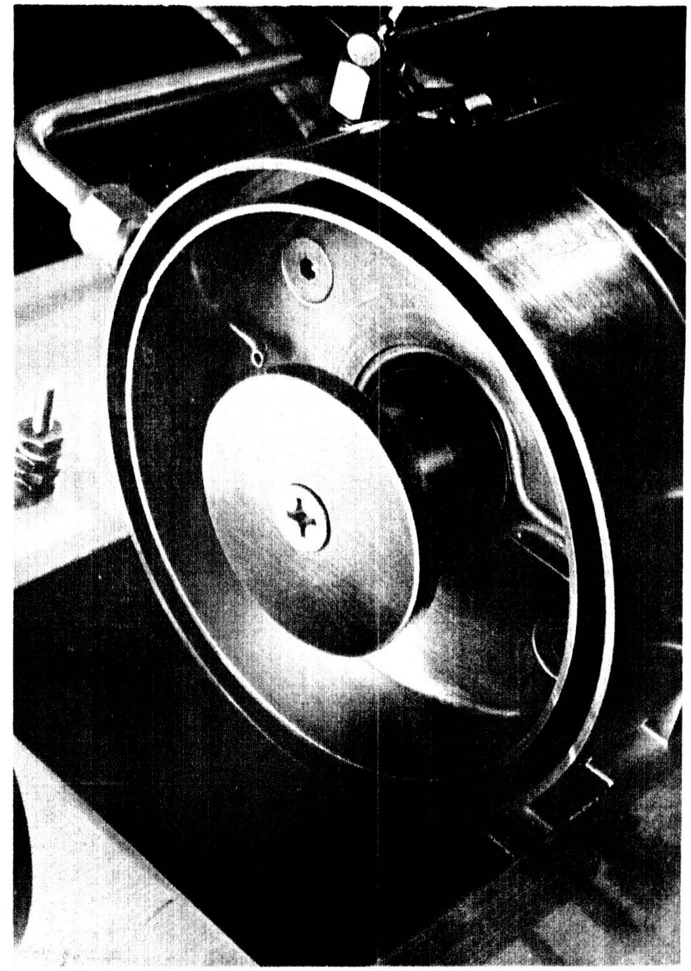

Figure 26. Cup-Cover Flange Showing Disk

A one-horsepower variable-speed motor drives the spindle to speeds up to 7600 rpm. Isolating the motor supports with dampers helped reduce vibration through the frame. A machined pulley was also necessary for smooth spindle rotation. An O-ring drive belt was found to be more satisfactory than a light-weight V-belt. The spindle housing cavity was sealed at both ends with lip seal cartridges. The material in the lower seal was Viton and the upper seal was neoprene. A single coil, cooled by water, surrounds the spindle entrance into the cup-cover flange. Additional cooling of the bottom seal is accomplished by oil circulating through the spindle housing. This oil flow (250 cc/minute) effectively lubricates the bearings and dissipates most of the heat from the spindle.

Attached to the spindle is a chuck holding the rotating test disk. The chuck face is accurately machined perpendicular to the spindle axis. Test disk faces are ground parallel and perpendicular to the concentic hole. The test disks are then easily attached interchangeably to the chuck. An alternate design used a chuck holding a ball to which the disk was attached. This latter arrangement permitted limited motion of the disk in all directions. However, the alternate method of disk attachment had to be abandoned because of the vibrations induced.

Three 1/4-inch diameter balls are held stationary and equidistant in the test cup. A plate with the positioning holes, through which the balls protrude, is held tightly with a screwed down hold ring. The outer well of the cup contains Cerrobase, a low melting alloy that serves as a hermetic seal during purging. The adjacent well contains a quantity of test fluid as a buffer in preventing contamination of the center well by the Cerrobase.

A thermocouple is inserted into a well adjacent to the balls and serves to control the fluid temperature. A torque arm is attached to the cup. Three heater cartridges totalling 900 watts heat the cup. A heat insulator separates the cup and air bearing plate. The air bearing is no longer being used.

The cup assembly is supported at its center by a conical pin mounted on a pneumatically operated piston. Rider-on-disk contact loads of one pound or more are accurately measured with a mercury manometer. The accurate alignment between spindle housing and piston housing is essential to even wear on the rider-on-disk rubbing surfaces.

The inert gas system (Figure 27) comprises a nitrogen gas source, gas purifier, cup cavity that is being purged of air, and oxygen analyzer. Commercial grade nitrogen, used as a source of inert gas, is purified by passing through hot NaK. Purified nitrogen, at 2 psi, flows through the cup cavity. The cup is hermetically sealed by the Cerrobase, which is a solid at room temperature. During the purging stage, the air above the degassed fluid in the reservoir is also purged. The use of vacuum in speeding the purge process proved unnecessary because of the small volume in the system.

The contamination level in the system is measured by a Beckman Model 80 oxygen analyzer. After acceptable oxygen levels are obtained (below 50 ppm) the nitrogen pressure is reduced and maintained at less than one inch of water. The control settings of temperature, time, speed, and load are adjusted and the test is run. The automatic control features of the original Shell 4-Ball Wear Tester are retained in this test setup. Tests will be conducted on those bearing material combinations listed in Table 32. The optimum bearing material combination for each fluid will then be coordinated with the NASA Program Manager and employed as bearings in pumps used in Task III.

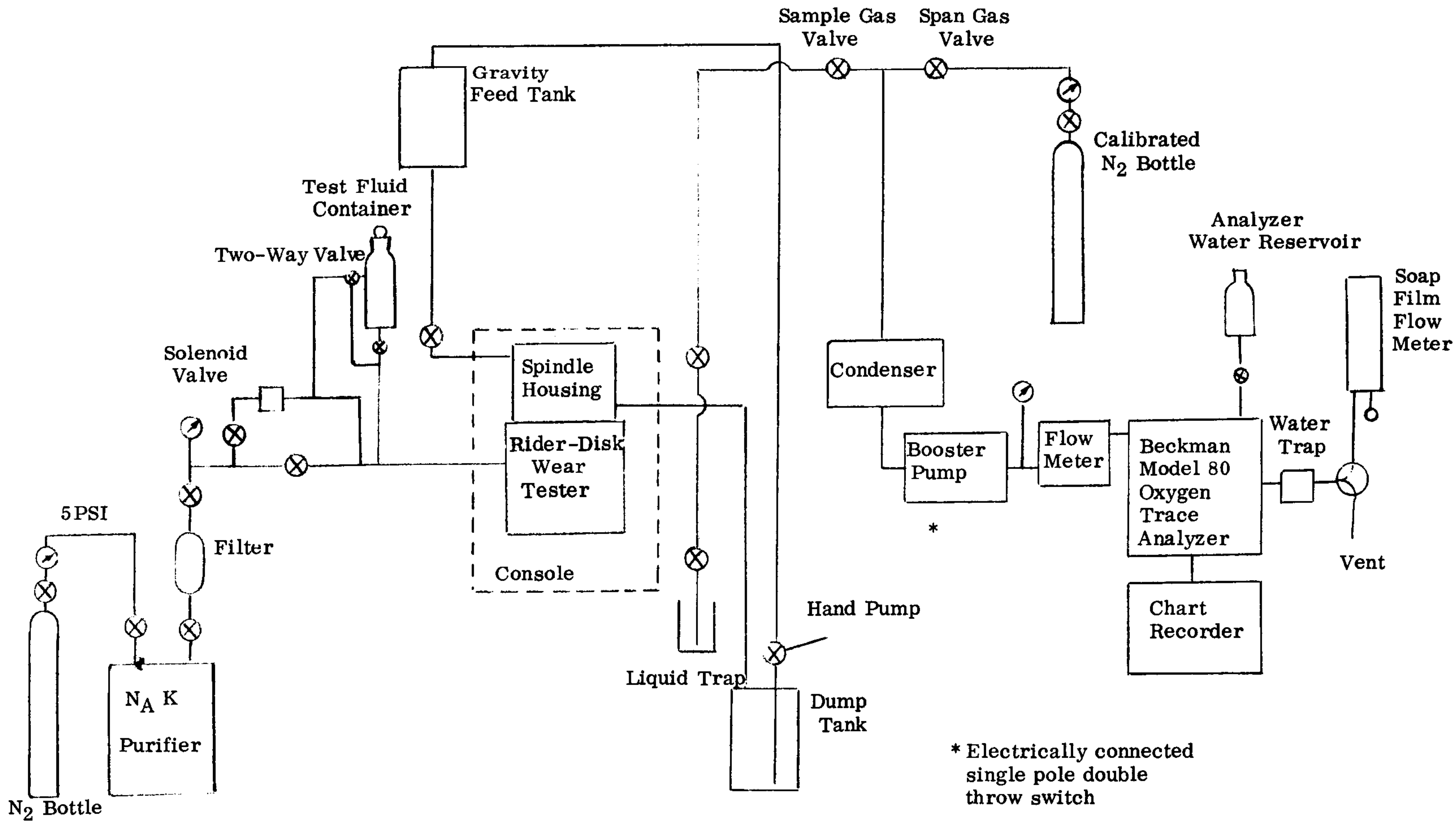

Figure 27. Schematic of Inert-Gas System

TASK III - SIMPLE PUMP LOOP TESTS

The five candidate fluids will be run in a simple 3000-psi pump loop. Pump bearings for each fluid will be those selected in Task II. Four gallons of degassed fluid under cover of purified nitrogen will be tested in the system. Each fluid will be run for 50 hours (or until pump failure) at each of the test pump inlet temperatures of 400°F, 500°F, and 600°F. The pump will be cycled in the range of 0.5 to 8.0 gallons per minute at each temperature.

Tests at temperatures of 450°F and 550°F for 20 hours at each temperature may be conducted with the approval of the NASA Program Manager. Fluid sample recovery and pump disassembly will be conducted at each temperature level.

Simple pump loop tests will be conducted as shown in Figure 28 - Schedule For the Next Six Months.

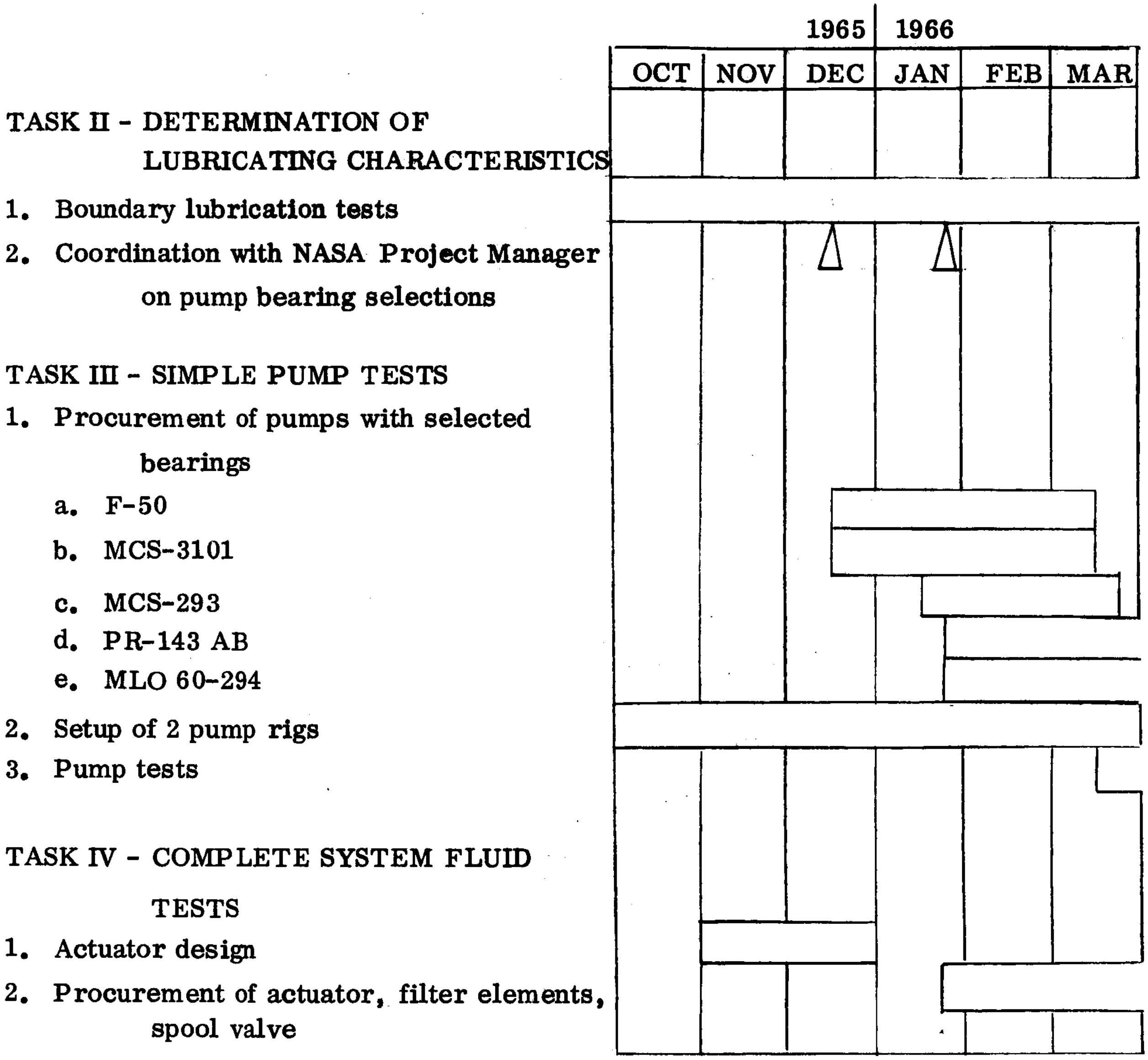

Figure 28. Schedule for the Next Six Months

TASK IV - COMPLETE SYSTEM FLUID TESTS

Two fluids that show the best performance in Task III will be endurance tested for 3000 hours at a pump inlet temperature of up to 600°F with a hotspot temperature of 650°F. In addition to the pump system of Task III, an actuator, a loading device, and filters with different micronic ratings will be used. The system will be monitored to determine fluid behavior changes.

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24. NASA TMX-52096, Friction and Wear of Hexagonal Metals and Alloys as Related Structure and Lattice Parameters in Vacuum to 10^{-10} Millimeter of Mercury, D.H. Buckley and R.L. Johnson

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APPENDIX I

CORRESPONDENCE: REPUBLIC AVIATION AND DUPONT

OR-8684

EXHIBIT "A"

APPENDIX I

E. I. DU PONT DE NEMOURS & COMPANY
INCORPORATED
WILMINGTON 98, DELAWARE

ORGANIC CHEMICALS DEPARTMENT

August 24, 1965

Mr. Frank Damasco
Republic Aviation Corporation
Farmingdale, Long Island, New York

Dear Mr. Damasco:

Dr. Finn has asked me to send you as much information as we presently have available on the bulk modulus, thermal conductivity, and specific heat on our PR-143 fluorocarbon functional fluids, as you requested in a recent telephone call. We appreciate your interest and are anxious to provide any information we have which may be useful to you.

The isothermal secant bulk modulus data we have on these fluids is given in the attached table.

Available thermal conductivity measurements on the PR-143 fluids are given below:

Temperature, °F	Thermal Conductivity, BTU/hr-ft^2-°F/ft. PR-143AA	PR-143AC
100	0.049	0.0537
300	0.046	0.0508
500	(Too volatile)	0.0508

Specific heat measurements on the PR-143 fluids are presented below:

Temperature, °F	Specific Heat PR-143AA	PR-143AC
100	0.243	0.226
200	0.257	0.249
300	0.272	0.272
400	0.287	0.295
500	0.302	0.317

With regard to the toxicological and hazardous properties of the PR-143 fluids, we must advise that these have not been fully investigated. Our Haskell Laboratory has conducted tests with rats and rabbits which led to the conclusion that PR-143 fluids are, in general, of very low toxicity when used at room temperature. Lethal doses could not be attained nor was there pathologic change

BETTER THINGS FOR BETTER LIVING . . . *THROUGH CHEMISTRY*

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- 2 -

when the material was administered intragastrically to rats, or by skin absorption to rabbits. It was not significantly irritating to the skin or eyes.

If the oil was inhaled by rats, either as a mist at room temperature or as a mixture of mist and pyrolysis products at high temperatures, the droplets could be found in the lungs 14 days after exposure surrounded by macrophages which is a typical tissue reaction to a foreign body. When the oil was taken to high temperatures (700°F) there was, in addition, evidence of the beginning of scar tissue formation; possibly indicative of injury from one or more of the breakdown products. Ten 4-hour exposures to oil kept at 500°F produced no clinical signs, but oil droplets were found in the lungs.

Until more definitive information becomes available, we recommend that, whenever fluids of this type are handled above 450°F, efficient and continuous ventilation be employed to avoid any exposure of personnel to potential decomposition products.

Please let us hear from you again if you desire any further information on these fluids.

Very truly yours,

Neal D. Lawson

Neal D. Lawson
Development Specialist

NDL/mec
Attachment

cc: Dr. George A. Finn

APPENDIX I (Cont'd)

THE EFFECT OF TEMPERATURE AND PRESSURE ON THE BULK MODULUS OF PR-143AB and PR-143AC

Temperature, °F	Pressure, psig	Isothermal Secant Bulk Modulus, psi PR-143AB	PR-143AC
70	1,000	138,600	-
	3,000	150,500	-
	5,000	162,200	-
100	1,000	125,000	-
	2,000	-	135,300
	3,000	137,000	-
	5,000	149,000	153,700
	10,000	-	184,500
210	1,000	82,300	-
	3,000	94,000	-
	5,000	106,000	-
335	1,000	48,800	-
	2,000	-	57,840
	3,000	60,500	-
	5,000	72,300	-
425	1,000	32,000	-
	3,000	43,700	-
	5,000	55,500	-

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8/24/65

APPENDIX II

EXHIBIT "A"

SCOPE OF WORK

The Contractor shall furnish the necessary personnel, facilities, services and materials and do all things necessary for, or incident to, the work described below:

The work to be performed shall consist of the evaluation of a number of hydraulic fluids under operating conditions appropriate for use in advanced supersonic aircraft, with a target of 3000 hours of maintenance free high temperature operation.

The work shall include the following Tasks:

TASK I - Determination of Physical and Chemical Properties of Selected Fluids

A. The five fluids listed below, one of which shall be the reference fluid, shall be used by the Contractor:

1. Reference fluid - chlorinated phenyl methyl silicone, General Electric Co., F-50

2. Super refined mineral oil - MLO-60-294

3. Monsanto Co. - modified polyphenyl ether - MCS 293

4. Monsanto Co. - halogenated polyaryl fluid - MCS 310

5. Fluorocarbon polymer - DuPont fluid, PR 143-AB

B. Laboratory evaluation of the five degassed fluids shall be made to obtain data on the following properties:

1. Thermal stability

a. Differential thermal analysis shall be obtained.

b. Thermal stability shall be determined in the Contractor's thermal stability test equipment as follows:

(1) A 30 ml sample of fluid shall be sealed in a stainless steel tube in a nitrogen atmosphere and heated to 600°F for ten (10) hours. The fluid shall then be cooled; neutralization number, viscosity and appearance shall then be recorded. This test shall be repeated

with fresh fluid at 50^{o}F increments until an appreciable change in properties has been determined by the Contractor to have occurred.

2. Fire resistance

   a. Hot manifold and spray ignition tests shall be made as follows:

      (1) In the hot manifold tests, the test fluid shall be dropped on a pipe heated to 1200^{o}F to determine if ignition occurs.

      (2) In the spray ignition test, fluid shall be sprayed from an orifice with a flaming torch applied to the spray at varying distances from the orifice to determine if ignition occurs.

3. Bulk modulus

   a. Bulk modulus shall be determined on fluids up to and including 600^{o}F.

4. Kinematic viscosity

   a. Shall be determined at -40^{o}, -20^{o}, 0^{o}, 100^{o}, 210^{o}, 400^{o}, 500^{o} and 600^{o}F.

   b. Kinematic viscosity at temperatures up to 400^{o}F shall be determined per ASTM D-445.

   c. Viscosities at temperatures up to 600^{o}F shall be determined in a constant-boiling liquid bath.

5. Acid number

   a. Acid number shall be determined per ASTM D-664.

6. Autogenous ignition temperature

   a. Autogenous ignition temperature shall be determined per ASTM D-286.

7. Flash point

   a. Flash point shall be determined per ASTM D-92.

APPENDIX II

EXHIBIT "A"

SCOPE OF WORK

The Contractor shall furnish the necessary personnel, facilities, services and materials and do all things necessary for, or incident to, the work described below:

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with fresh fluid at 50°F increments until an appreciable change in properties has been determined by the Contractor to have occurred.

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(2) In the spray ignition test, fluid shall be sprayed from an orifice with a flaming torch applied to the spray at varying distances from the orifice to determine if ignition occurs.

3. Bulk modulus

a. Bulk modulus shall be determined on fluids up to and including 600°F.

4. Kinematic viscosity

a. Shall be determined at -40°, -20°, 0°, 100°, 210°, 400°, 500° and 600°F.

b. Kinematic viscosity at temperatures up to 400°F shall be determined per ASTM D-445.

c. Viscosities at temperatures up to 600°F shall be determined in a constant-boiling liquid bath.

5. Acid number

a. Acid number shall be determined per ASTM D-664.

6. Autogenous ignition temperature

a. Autogenous ignition temperature shall be determined per ASTM D-286.

7. Flash point

a. Flash point shall be determined per ASTM D-92.

8. Fire point

   a. Fire point shall be determined per ASTM D-92.

9. Pour point

   a. The pour point shall be determined per ASTM D-97.

10. Density

   a. Density shall be determined in the range of 0° to 600°F.

   b. Density shall be determined by means of a modified version of ASTM D-941, to be recommended by the Contractor and approved by the NASA Project Manager.

11. Coefficient of expansion

   a. This property shall be determined in the range of 0° to 600°F.

   b. Coefficient of expansion shall be determined by means of a modified version of ASTM D-941, to be recommended by the Contractor and approved by the NASA Project Manager.

12. Specific heat

   a. Specific heat shall be determined in the range of 0° to 600°F.

   b. Refer to paragraph "C.", below.

13. Thermal conductivity

   a. This property shall be determined in the range of 0° to 600°F.

   b. Refer to paragraph "C.", below.

14. Vapor pressure

   a. Vapor pressure shall be determined in the range of 0° to 600°F.

   b. This property shall be determined from the differential thermal analysis test. Refer to paragraph "B.1.", above.

15. Nitrogen solubility

   a. This property shall be determined by means of gas chromatography.

16. Compatibility

    a. Compatibility shall be determined with system materials, seal materials and engine oils.

C. Fluid manufacturers' data may be used with specific approval of the NASA Project Manager. Where specific methods of obtaining fluid properties have not been defined, those in use at Pennsylvania State University Petroleum Refining Laboratory under Air Force Contract AF33(616) 7590 shall be acceptable.

D. All ASTM specifications referred to herein are incorporated herein by reference and hereby made a part hereof.

TASK II - Determination of Lubricating Characteristics

A. The boundary lubricating capabilities of the five fluids tested in TASK I shall be measured using four material candidates for the sliders, selected from materials appropriate for a pump and other hydraulic system components for 600°F operation. The choice of material-fluid combinations shall be subject to the approval of the NASA Project Manager. Wear and friction data (including dynamic friction coefficient and volumetric wear data) of the selected twenty material-fluid combinations shall be evaluated at 400°, 500° and 600°F over the surface speeds of 1000, 2000 and 3000 fpm and maximum stress levels encountered in hydraulic systems. Atmospheric controls shall be used to assure inerting. Nitrogen gas (99.99 per cent by volume N_2) containing not more than 50 ppm oxygen and 5 ppm hydrocarbon (as methane) and having a dew point of -90°F or lower shall be used as the cover gas. Prior to testing, the fluids shall be degassed by subjecting them to a pressure of 10^{-3} mm of mercury and temperature between 200° and 240°F for seventy-two (72) hours, or as otherwise approved by the NASA Project Manager.

B. The boundary lubricating capabilities of two (2) fluids selected by the NASA Project Manager, from the five fluids tested in TASK I, shall be evaluated with their optimum bearing materials, using a cover gas having 100 ppm and 1000 ppm oxygen content at 600°F and at surface speeds of 1000, 2000 and 3000 fpm.

C. The surface appearance, as well as the friction and wear data, shall be documented. Specimens shall not be altered after test without prior examination by and/or approval of the NASA Project Manager.

TASK III - Simple Pump Loop Tests

A. The five fluids tested in TASK I shall be run in a simple pump loop. A positive displacement pump which provides an outlet pressure of at least 3000 psi with a reservoir pressure of 50 psi shall be used. The system capacity shall be no more than five gallons, and the system shall not contain air. The test fluids shall be degassed and evacuated to 10^{-3} mm of mercury prior to each test. Nitrogen having the characteristics stated in TASK II shall be used as a cover gas. The system shall provide for flow control and flow and temperature measurement. A heat exchanger shall be provided between a flow restrictor (orifice) and the reservoir to maintain desired reservoir temperatures. Flows in the range 0.5 to 8.0 gallons per minute shall be achieved and periodic flow cycling shall be included in the test procedure. Each test fluid shall be run 50 hours (or until failure of the pump) at each of the test pump inlet temperatures 400°, 500°, and 600°F, in that order. Intermediate values of temperature and/or shorter running times can be used with the approval of the NASA Project Manager. Seals and other system materials shall be optimized for the fluids selected and shall be subject to the approval of the NASA Project Manager.

B. Fluid samples shall be taken for analysis at 5, 10, 20, 30, and 50 hours, as a minimum, for each test of TASK III, subparagraph A. Minimum data to be obtained for each sample shall include kinematic viscosity at 100° and 210°F and the acid number. The pump shall be disassembled at the end of each temperature level of operation and shall be examined for wear, surface failure and corrosion. Operation at the subsequent temperature level shall be without change to the pump and without the addition of new fluid unless specifically approved by the NASA Project Manager. Evidences of wear and deposits in pumps shall be documented photographically at the end of each temperature level of operation. Quantitative wear data shall be obtained. All deposit types found in the system shall be chemically analyzed. Efforts shall be made to establish mechanisms of fluid degradation for test fluids using conductivity measurements, infrared spectrography techniques and other common laboratory methods.

TASK IV - Complete System Fluid Tests

A. Two fluids from among the five fluids tested in TASK I shall be selected by the Contractor with the approval of the NASA Project Manager for evaluation in a complete test system. The test system shall contain servo valves, actuators, loading devices and any other general types of hydraulic equipment that are required for the operation of a complete hydraulic system. Four stainless steel filters with different pore diameters (5, 10, 15, and 20 microns) shall be installed in parallel in the system. Each filter shall be capable of handling the entire flow of the system. Controls shall provide for changing the flow from one size filter to the next larger size filter when the pressure drop across the working filter exceeds a value to be determined by the Contractor with the approval of the NASA Project Manager. The system shall be free of air and the test fluids shall be degassed prior to operation. A nitrogen cover gas with the requirements stated in TASK II shall be used. The system shall operate at pressures up to 3000 psi with fluid temperatures at the pump inlet up to 600°F with a hotspot temperature of 650°F. The system fluid capacity shall be approximately four (4) gallons. Separate systems shall be provided for the two test fluids so that concurrent runs can be made. Seals and other system materials shall be optimized for the fluids selected and shall be subject to the approval of the NASA Project Manager.

B. The values of system temperature and pressure to be used for testing each of the fluids shall be selected on the basis of the results of TASK III with the approval of the NASA Project Manager. The system shall be operated for each fluid for a period of 3000 hours (or until the NASA Contracting Officer shall declare the test to be terminated at a time less than 3000 hours). Fluid samples shall be obtained after 50, 150, 500, 1000, 1500, 2000, 2500 and 3000 hours of operation and the kinematic viscosity at 100°F and at 210°F and the acid number shall be determined.

C. The tests described in TASK II shall be carried out for fluid samples from the complete system tests to determine the lubricating characteristics of the test fluids after 500, 1000, 2000 and 3000 hours of operation. The material from which the primary sliders are made shall be the same as for a given fluid for all tests made under TASK II.

D. The force necessary to actuate a spool valve operating in the system shall be measured continuously during the test. Every component used in the system, including all lubrication surfaces and seals, shall be examined for evidence of wear at the conclusion of the test.

GLOSSARY

PR-143AB	Fluorocarbon fluid developed by DuPont. The AB or AC suffix indicates hydraulic or engine grades, respectively.
MLO 60-294	Deep dewaxed superrefined paraffinic base oil developed by the Petroleum Refining Laboratory of Pennsylvania State University
FN 3160	Humble Oil and Refining Company's version of MLO 60-294
HTHF 6294	California Chemical Company's version of MLO 60-294
MCS-310	Halogenated polyaryl fluid developed by Monsanto Company
MCS-3101	MCS-310 with a probable corrosion type inhibitor added to the fluid
MCS-293	Modified polyphenyl ether fluid produced by Monsanto Company
F-50	Chlorinated phenyl methyl silicone produced by General Electric Company
XRM-154	Alkylated silicone fluid produced by Socony Mobil Oil
XF-1-0288	Copolymer of trifluoropropyl and bromophenylmethyl silicone. A product of Dow Corning Corporation
XF-1-0291	XF-1-0288 with a defoamer
XF-1-0294	Trifluoropropyl methyl polysiloxane fluid developed by Dow Corning Corporation
B88A/64	Brominated hydrocarbon-ester mixture formulated by Castrol
ETO 5251	Ester base engine grade oil produced by Humble Oil and Refining Company
Synthetic 18H	Polyolefin oil developed by Sun Oil Company
HTHF 70	Silicate ester fluid produced by California Chemical Company
K-82	Tungsten-titanium carbide produced by Kennametal
K-96	Tungsten carbide with 6% cobalt binder produced by Kennametal

K-162B	Tungsten-titanium carbide with nickel binder produced by Kennametal
Dynalloy 600	Bronze bearing material produced by Mueller Brass Co.
Pheldor 10	Iron-silicon-bronze produced by Phelps Dodge
Voi-Shan seal	Produced by Voi-Shan Manufacturing Company
H-film	High temperature plastic developed by DuPont
Cerrobase	Low melting alloy produced by Cerro de Pasco Corporation
NM-100	High temperature bearing material; produced by Nuclear Metals Division of Textron, Inc.

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